



INFRARED IMAGERY OF SHUTTLE (IRIS) EXPERIMENT
IRIS/STS-3 ENGINEERING REPORT
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INFRARED IMAGERY OF SHUTTLE (IRIS)/STS-3 ENGINEERING REPORT

1.0 INTRODUCTION

The IRIS/STS-3 Engineering Report describes the results of the various multidisciplinary efforts which culminated in the successful imaging of the STS-3 vehicle during its reentry. The success of the mission was largely due to the intensive and dedicated team effort which involved personnel from Ames Research Center; Johnson Space Center; Goddard Space Flight Center; Ninth Strategic Reconnaissance Wing, Beale Air Force Base, California; 2762nd Logistics Squadron, Palmdale, California; Western Test Range, Vandenberg Air Force Base, California; Army Electronics Proving Ground, Fort Huachuca, Arizona; USAF 2045th Communications Group, Andrews Air Force Base, Maryland; and Martin Marietta Corporation, Denver, Colorado.

Specific details for each major effort of the mission are described in the following appendices of this report:

Appendix 1.0	Summary of IRIS Hardware and Software Changes
Appendix 2.0	IRIS System Report
Appendix 3.0	IRIS Hardware Report
Appendix 4.0	IRIS Software Report
Appendix 5.0	IRIS Mission Operations Report
Appendix 6.0	IRIS/KA0 Operations Report
Appendix 7.0	IRIS Radiometer Analysis Report

This report does not address the IRIS data reduction and analysis of the image which will be the subject of a separate report to be issued at a later date.

2.0 SUMMARY

The image of the STS-3 vehicle was obtained using the encounter geometry described below with STS-3 banked as shown in Figure 1.

Encounter Time: EI + 16.5 minutes where Entry Interface (EI) is defined as an altitude of 400,000 feet.

Acquisition Range: 264,000 feet.

Boresight Range: 169,700 feet.

Time to Boresight (Initial Acquisition to Boresight): 16 seconds.

Altitude of STS-3: 182,000 feet.

Relative Velocity of STS-3: 13,463 feet per second.

Angle of Attack of STS-3: 40°.

Tracker Look-Back Angle: 50°.

KA0 Telescope Elevation: 55°.

Altitude of KA0: 41,000 feet.

Reentry Orbit: Orbit 130 into Northrop.

Approximately 60 percent of the STS-3 image was obtained. Failure to obtain the entire image is still under investigation, but there is sufficient evidence to indicate that a misalignment between the tracker telescope and the KA0 telescope was primarily responsible for the partial image. A detailed discussion of the misalignment problem is presented in Appendix 3.0.

The estimated signal strength at encounter was approximately 3.5 times higher than expected. Investigation of this discrepancy has indicated that the laboratory setup used for the preflight calibrations was inaccurate and has now been corrected. Appendix 3.0 contains the calculations to substantiate this theory.

Previous concerns relative to the intermittent motor noise (see Appendix 3.0), crosstrack margin (see Appendix 2.0), and KA0/IRIS system constraints (see Appendices 1.0 and 6.0) did not affect the IRIS/STS-3 mission primarily due to the results of the intensive teamwork and coordination done in preparation for the mission; however, these elements are still valid concerns; they have the potential for impacting the success of future missions; and, they need to be resolved if IRIS is to be made operational for future STS flights.

3.0

RECOMMENDATIONS

The results of the IRIS/STS-3 mission and an analysis of the future flight opportunities for IRIS have disclosed several system engineering weaknesses which must be resolved before IRIS can be considered as an operational program. Most of these system weaknesses such as crosstrack margin, sensitivity, and real-time data communications can be resolved, although not in an optimum manner, if the IRIS encounter point is always selected prior to any STS reentry maneuvers. However, this constraint limits the usefulness and versatility of IRIS and minimizes the potential for obtaining equally valuable data in the late transitional region (after EI + 18) and the fully turbulent region (EI + 20 and beyond).

To address these issues, it is recommended that funds be provided to conduct an end-to-end system optimization study which will result in the improvement of the overall system performance capability by at least a factor of 2. The decision to proceed with the implementation of the study results into system hardware will be decided at the conclusion of the study and will consider tradeoffs such as overall costs and schedule, cost-effectiveness of the proposed design improvements relative to science return and probability of mission success for each flight independent of the STS flight profile, and resources required to implement and evaluate the design changes.

Estimated funding required for the design study is \$75K for a 12 calendar month effort.

A peak heating encounter (EI + 6) is planned for STS-4. (No maneuvers which affect IRIS are planned prior to EI + 6). In order to maximize the probability of success for this mission, the following tasks will be done:

- a. Intensive coordination and interaction with the mission planning and support elements used for the STS-3 mission, i.e., JSC, AF Communications Network, AF Tracking Network, and ARC.
- b. Procedural changes to prevent the misalignment problem.
- c. Continued investigation and implementation of corrective actions, if appropriate, for the motor noise, faster acquisition, and handling of real-time flight data.
- d. Recalibration of the laboratory calibration setup and the IRIS array.

There are no known contingencies at this time which will affect the success of IRIS for the STS-4 mission.

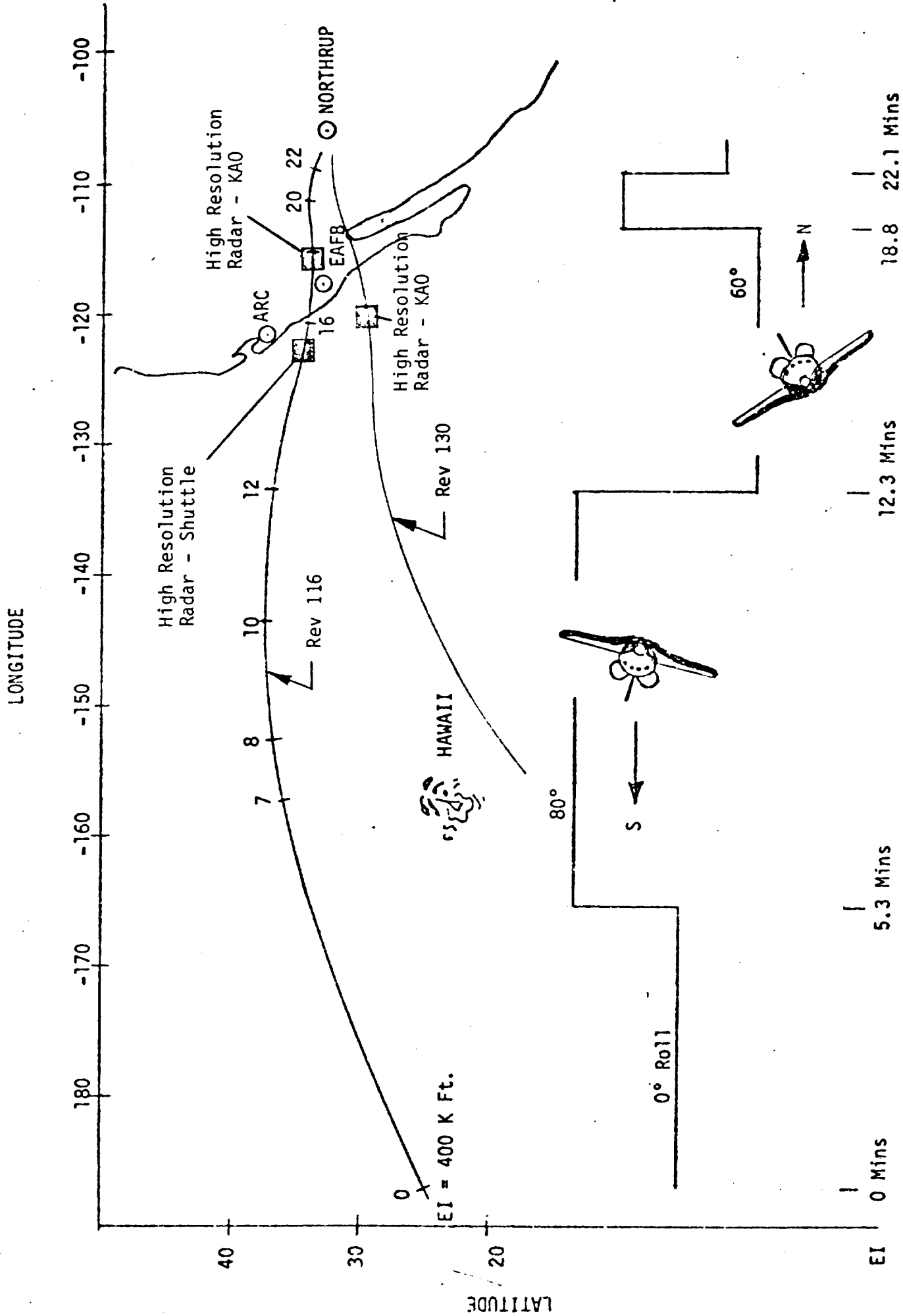


Figure 1

APPENDIX 1.0

SUMMARY OF IRIS HARDWARE AND SOFTWARE CHANGES

1.1 IRIS TECHNICAL CHANGES - HARDWARE

1.1.1 January 1981 to STS-1 (Equipment transferred to SPT in January 1981)

1. New detectors with Ge window installed to reduce sky background flux.
2. Installed nitrogen purge tube to prevent lens from icing during flight.
3. Redesigned cryostat holder for better contact with detector.
4. Designed an electronic circuit to reject sky background noise.
5. Redesigned the power amplifier circuits (reticle and gimbal motors) to eliminate oscillations.
6. Developed new alignment procedure for the IRIS telescope and the KAO telescope.

1.1.2 STS-1 to First of SR-71 Flights (April 1981 to early September 1981)

1. Designed an AGC circuit to reduce the misalignment between the tracker and the KAO telescope due to changes in signal strength.
2. Modified the laboratory test jig for the tracker to simulate the Shuttle as an accelerating target rather than a constant velocity target.
3. Replaced three integrated circuits with new designs to correct system malfunctions under certain conditions.
4. Added additional circuits to correct the 30 degree "glitch" problem in the tracker.
5. Repackaged the gurley amplifier printed circuit board and rewired the tracker cable harness for increased reliability.
6. Replaced the glass reticle with a sapphire reticle to reduce the tracker's signal transmission loss.
7. Changed the tracker detector bandwidth from 2 to 2.5 microns to 3 to 4 microns to reduce sky background noise.
8. Replaced the glass condenser lens with silicon for a 9-fold increase in signal.
9. Added additional circuits for performance data analysis.
10. Redesigned image plane threshold circuits.

11. Redesigned anti-backlash mechanism for the gimbal gear.
12. Designed a tester which permitted testing of IRIS with a moving target while integrated to the KAO.

1.1.3 Post SR-71 to Present (Pre-STS-2)

1. Redesigned condenser lens to obtain 9 degree FOV.
2. Modified tester's capability for increased FOV testing of the tracker.
3. Fabricated new gear for the tracker system.

1.2 IRIS TECHNICAL CHANGES - SOFTWARE

1.2.1 Post STS-1/Pre-SR71 Encounter (Prior to STS-2)

A. Tracking Software

1. Corrected routine which checked timeouts between IRIS hardware and software and restructured calling code to count timeouts rather than halt the tracking software.
2. Added a subroutine which output the raw errors in azimuth and in elevation to the IRIS hardware so that they could be written in analog form to a stripchart recorder.
3. Implemented a smoothing function of the raw error in azimuth before it was put into the control system.
4. The software was modularized and restructured.
5. The ability to selectively use the printer was added.
6. The diurnal rate code was removed.
7. The ability to change the default constants and retain new values for all subsequent runs was implemented.
8. An integrator was added in the azimuth loop to allow the tracker to keep pace with an accelerating source.
9. The logic of the azimuth loop was altered to allow the tracker on initial acquisition to remain motionless until the source was well within the limits of its maximum "seeing" capability.

1.2.3 Post-SR71 Encounter (Prior to STS-2)

A. Tracking Software

1. New smoothing algorithm for input errors both in azimuth and elevation.
2. Ability to select two of the following errors for conversion to analog form to the stripchart recorder:

Raw error in azimuth, smoothed error in azimuth.
Raw error in elevation, smoothed error in elevation.
3. The prompting menu was split into two menus for easier readability.

1.2.4 Pre-STIS-3

A. Tracking Software

1. Rewrite the elevation control, including ramp up and ramp down.
2. Made the phase rotation error constant an input variable.
3. A subroutine was added that determines if there are dropouts in the input radius. If there are 3 dropouts out of 15, a flag is set and no elevation rate is put out to the KAO telescope until the noise dropouts are less than 3 out of 15.

APPENDIX 2.0

IRIS SYSTEM REPORT

T. L. Grant

2.0 Conceptually, the experiment to obtain an infrared image of the Shuttle is easy to understand. A linear array of IR detectors and a tracker are added to the Kaiper Astronomical observatory (KAO) telescope, and the KAO rendezvous with the Shuttle. The tracker then follows the Shuttle as it approaches and guides the telescope to the proper elevation such that the Shuttle image crosses the array and is recorded. Why then should it be so difficult that the first image was only obtained on the third Shuttle re-entry? Like many other concepts, the realization requires a few quantitative conditions that are not obvious at first glance. To help visualize the breadths of these conditions, let me refer you to what I call the "IRIS Probability of Success," Figure 1.

Without detailing all the possible mistakes and capricious events which can keep one from reaching its core, I'll briefly describe its many layers:

- (1) The Shuttle re-entry trajectory and attitude must be such that the KAO can predict a rendezvous for an unrestricted airspace which allows a view in a direction facing away from the Sun.
- (2) Because of restricted tracker acquisition field-of-view, F.O.V., and limited telescope slewing rate, the Shuttle trajectory must be refined and the updates communicated to the KAO in the last few minutes before the rendezvous.
- (3) The inertial position error of the KAO can reduce the probability of acquisition, so it too has been updated by precision radar and communicated.
- (4) The KAO position is then recomputed and adjusted during the final minutes (including a decrab maneuver and allowance for crosstrack wind).
- (5) The telescope pointing must then be recomputed and steered to the optimum elevation for signal acquisition and tracking.
- (6) The tracker will acquire if the Shuttle signal is above background noise of its temperamental sensor and within its +4° F.O.V.
- (7) This should activate two complex, digitally-controlled feedback loops allowing the tracker to follow the signal azimuth while the main telescope elevation error is pulled toward a null in the last seconds.

- (8) The tracker and telescope must be aligned to within a couple of arc minutes in elevation to bring the image across the detector array.
- (9) The array of hundreds of detectors at liquid nitrogen temperature must have their signals amplified by 200 amplifiers, then multiplexed, digitized via 20 converters, and summed digitally to trigger the loading of a semiconductor memory at a rate of 48 Mbps.
- (10) The telescope must be focused on the array under the low temperature conditions of high altitude.
- (11) The atmospheric turbulence must not significantly disturb the IR propagation over the Shuttle range of more than thirty statute miles.
- (12) After the image memory has been successfully loaded, it must be transferred to magnetic disk and tape along with array calibration data.
- (13) Finally, the first image reconstruction can be started, and the data processed into temperature profiles.

Time doesn't permit a review of the early history of IRIS, its failures, and the corrective measures taken, but many of the design changes were aimed at probability layers 6 through 9.

After the complete miss with STS-2 because of a large crosstrack error (Layer 1), an expanded planning and operations effort was begun with the aid of Dryden and Johnson Space Flight Centers.

It was also decided after STS-2 that a new procedure and computation was needed to command the telescope to an optimum elevation for acquisition of the tracking signal. This plan was aimed at supporting an SR-71 rendezvous, which was needed to provide a system test and rehearsal for the STS-3 mission. Thus, the KAO operations monitor computer was programmed to keep track of the rendezvous geometry. It allows updates of encounter time, desired crosstrack position, altitude difference, etc. Furthermore, it automatically samples actual wind and aircraft position directly from the KAO's Inertial Navigation System (INS). The main program outputs are directed to the telescope operator. One predicts the optimum elevation for acquisition at the expected encounter time. The other predicts the optimum elevation at each instant to provide the best chance for acquisition if the encounter is either early or late. Thus, the telescope operator has an optimum target elevation to steer to at all times during the rendezvous. The procedure is that he steers the telescope in all three axis until the IRIS tracker acquires, then he releases control to the tracker.

During two days of test/rehearsals with SR-71's before STS-3 (March 23 and 24), we had three actual rendezvous, only one successful

track, and no image-plane detection. The first and third rendezvous got to Layer 6, the tracker acquisition. The second failed at Layer 2 when the encounter time was not properly communicated.

The first rendezvous failed at Layer 7 when the signal strength was too low to trigger the closing of the tracking loops.

The third rendezvous failed at Layer 7 when the elevation error could not be nulled until after the SR-71 passed the zero (boresight) azimuth angle. The elevation loop performed as expected, but the target elevation rate was beyond its capability due primarily to high crosstrack winds and the relative closeness of the SR-71 (approximately 6 miles). The crosstrack winds for STS-3 encounter were not expected to be so large. Also because STS-3 is much farther away, wind drift is not a large contributor to elevation error. Still, the nagging lack of a completely successful test remained.

The SR-71 tests served several important purposes:

1. They demonstrated two previously unsuspected weaknesses in SR-71 rendezvous. First, the potential for very low target temperatures, and second, the need for higher tracking rates under high crosswinds.
2. They demonstrated the value of the preacquisition elevation computer and its automatic wind and position updates.
3. They provided valuable rehearsal time for the KAO crew, and proved the value of a rehearsal run through the rendezvous area.
4. They pointed to a subtle adjustment of a parameter in the elevation tracking loop which should reduce the average time to null the elevation error for future missions.
5. They pointed to the need to account for azimuth effects of aircraft pitch when estimating the total tracking time to boresight.

With this last bit of added experience and information, the IRIS team had high hopes of a successful rendezvous with STS-3 on Monday, March 29. However, when the re-entry was delayed and new trajectory information was not available until late Monday, the probability of success waned. The perceived chances of predicting the trajectory of the Shuttle (Layer 1), and receiving good update information (Layer 2) seemed much less. Nevertheless, everyone put out their best effort, and the weeks of planning and reviewing paid off with some good luck for a change.

Precalibration for the STS-3 rendezvous included laboratory acceptance tests of the IRIS tracker with its tester, the IRIS image plane with its tester, and the IRIS software for both the tracker and image plane, (using a duplicate computer). This was followed on March 19 and 20 with dynamic and static checkout tests with the KAO in the hanger. Late March 20th the image plane was focused for the

expected SR-71 boresight range using the star Polaris and a calculated offset. Following the SR-71 test/rehearsals additional dynamic hanger checks were made on March 25th to verify that the elevation null rate could be improved by reducing one parameter (the elevation damp angle) and that a 30% increase in the maximum elevation rate command could be allowed without making the telescope drive unstable. (The second option was not exercised for the STS-3 rendezvous.)

On March 27th the final procedures were worked out for communicating the radar updates on the KAO and the STS-3 crosstrack position errors. Then an attempt was made to focus the image plane for the expected STS-3 boresight range using the star Polaris. (Recent inflight focusing attempts had failed because of sky brightness.) The weather didn't cooperate, however, and the focus was set in the hangar using a collimator. The following evening (Sunday) the weather cleared and the image plane focus was rechecked on the ground using Polaris.

On March 29th, well before the sun arose, some of the IRIS team and KAO personnel were cooling down the telescope chamber and running a final preflight check for the STS-3 rendezvous. At 6:45 a.m. all the flight crew was briefed for a possible "one-orbit-early" re-entry. Then we were rebriefed at 7:45 for the normal re-entry and took off at 8:40 expecting a rendezvous. During the rehearsal flight through the rendezvous area everything was nominal and the winds were out of the West as expected, causing virtually no crosstrack drift. A focus check at altitude was executed as planned (for a change) and everything seemed to be in readiness.... when word came in of the re-entry delay. We completed our planned course for rehearsal purposes and then returned to base. The extra rehearsals were useful, however, in allowing minor adjustments in procedures and communicating to everyone a sense of readiness.

On March 30th, still earlier than the sun, the preflight activities were repeated, except that now the navigator was hurriedly putting together a flight plan. Take-off was approximately 5:45 a.m., and the rendezvous area was approximately 150 miles south of Los Angeles. The people at Vandenberg, under the direction of a new IRIS team member, had worked up a new radar plotting board for this area a few hours earlier, so we hoped the Shuttle would actually follow this trajectory and land at White Sands.

We had reviewed the rendezvous geometry options and, since the delta altitude expected was only slightly more than the previous day, we elected to hold the nominal crosstrack at 16.3 nautical miles and the tracker azimuth at 50° (see table 1 and figure 2). The nominal elevation increased by 1.7° and the nominal acquisition margin reduced 20% to 1.8. The allowable crosstrack error for acquisition was approximately 3.3 nautical miles. The delta LOS and delta azimuth coordinates of the telescope were adjusted manually to compensate for the aircraft pitch and the elevation desired was adjusted by the operations monitor computer, thus accounting for updated crosstrack position as well as aircraft roll.

The actual time history of the computed elevation desired (1, MILO ELEV) and measured (2, TEL EL SK) are plotted in figure 3, along with the predicted elevation at the acquisition time (3 ACQ ELEV) and aircraft roll (4 ROLL). Inputs to the program and some ancillary parameters are shown in table 2. The plots are explained as follows: The radar updates to the KAO position were entered starting 45 minutes after the hour (15:45) and initially were not corrected for the latest STS-3 trajectory. Thus, the elevations are off the graph high until 48.5 minutes. At that point probability layer 3 was completed and layer 4 and 5 were in process. At that time, the aircraft was in the process of decrabbing as planned (note the peak roll of 2.5°). Approximately 20 seconds after the desired elevation (1) changes, the operator steers the measured elevation to within 1° , he then uncages the telescope and about 49.5 minutes after the hour the major events in layers 4 and 5 are completed as the operator tries to null the elevation error to within a fraction of a degree. Then at 50 minutes, 54 seconds acquisition is achieved (layer 6) and the tracker begins nulling the actual elevation error (layer 7). At 51 minutes, 9 seconds the error is less than 1 arc minute and at 11.56 seconds image detection is achieved completing layers 8 and 9 (see figure 4).

A significant problem occurred inflight when one of the telescope's three-axis reference gyros (the one for delta LOS) failed to operate. However, the mission was saved by the telescope crew; they set the nominal telescope position for the other two coordinates (elevation and delta azimuth) and made fine adjustments in the delta LOS balance to achieve the angle desired. The flight record shows that delta LOS was within 0.3° of its desired angle due to KAO pitch at acquisition when it has the most effect on the elevation error.* The effect at 50° tracker azimuth and 55° elevation is less than -0.4° in elevation error. The free-floating delta LOS axis could have caused a small unexplained variation in the elevation error (approximately 1 arc minute peak-to-peak) near boresight and also could be related to the slow nulling of the elevation error (see the discussion below).

The total measured elevation error at acquisition was $2.5^\circ \pm 0.2^\circ$ as measured in the IRIS tracker. This compares well with the change in elevation seen from the telescope engineering data (see figure 3) from 15:50:50 to 15:51:00. The elevation at boresight is estimated at $55^\circ \pm 0.5^\circ$.

The boresight time was within a half second of the predicted value: 15:51:11.5. However, the acquisition time was early by 4 seconds. Two factors contributed to the early acquisition: (1) The predicted time didn't allow for the extra 4° in the azimuth due to the F.O.V. and azimuth error; (2) The Shuttle reconstructed speed was about 10% less than predicted.

Using first cut estimates of the Shuttle altitude from radar and inertial data (181,000 ft) and the estimated image elevation of 55° , the boresight range was 171,000 ft and the crosstrack distance was 16.1 nautical miles. From the KAO engineering data the actual

crosstrack relative to the predicted Shuttle trajectory was 15.6 nautical miles.

- * The effect of heading error shows directly as elevation error for a tracker azimuth of 50° . It drops to 50% at an azimuth of 31° (after 10 seconds).

Therefore, the STS-3 was only 1/2 mile north of the predicted track. However, if we use the advertised plate scale of the telescope to calculate the boresight range, it was only 159,000 ft, and thus the elevation and crosstrack distance are less and the Shuttle was 0.6 nautical miles south of track. The difference in boresight range is 7% of which only 3% can be accounted for by error in the telescope focal length. More tests on the telescope itself are needed to resolve this difference.

The major weakness in the STS-3 rendezvous was the alignment error (layer 8) of -3 arc minutes (see Appendix 3.0).

The biggest surprise in the acquisition and tracking of STS-3 was the total flux received. It was approximately four times the estimated nominal low value. Apparently much of this difference is due to an improper calibration of the tracker because the calibration source was misaligned with its collimator lens. The total explanation of this requires some more analysis of the image itself as well as correlation with on-board measurements of the heat shield temperature.

A serious concern for future IRIS encounters is the significant amount of tracking time spent nulling the last 10 arc minutes of elevation error (the time spent in the "proportional" tracking mode of the elevation loop). Of the approximately 14 seconds spent coming to a null, about 9 seconds were spent closing on the last 10 arc minutes. The performance was that of a classical under-damped response, one which was never noted during any recent dynamic tests in the hangar. Out of the 9 seconds, 6 seconds were in non-linear control because the elevation rate command reached the maximum limit (the same problems noted above for the SR-71 track). This effect could have been eased if we had taken the less conservative approach and added 30% to that maximum.

To better understand the possible explanations for this effect it must be noted that the tracker elevation is a complex function of the KAO attitude and its own azimuth while the boresight elevation is mainly a function of the KAO roll and the telescope elevation relative to the KAO. At an azimuth angle of 40° , about 84% of the angular error in the azimuth plane of motion (LOS angle) shows up as elevation error. On the other hand for an azimuth angle of 20° or less, less than 20% of this motion shows up as elevation error. Since the LOS angle was not under gyro control it could have caused the high elevation rate requirements at moderate to large azimuth angles. The two-second-per-sample sequence of LOS angle (taken from the KAO operations data record) suggests that it was not inertially stable, but doesn't allow reconstruction of its actual motion.

Another possibility is that the telescope response characteristics changed at altitude from what has been measured in the hangar. Only additional flight tests can exclude this possibility.

In summary, the acquisition and tracking of STS-3 was a qualified success:

- (1) The tracking of STS-3 has been resolved to within 7% of the boresight range and more data analysis may narrow this error.
- (2) The IRIS tracker was found to be calibrated in error and has approximately three times more sensitivity than expected.
- (3) A bias error of 3 arc minutes was found in acquiring the image and appears to be due to a correctable alignment procedure.
- (4) The elevation error was slow to null out during tracking (possibly due to failed telescope gyro) and more in-flight and hangar testing is needed to verify the expected performance.

GEOMETRY OPTIONS FOR STS-3

	CT (NM)	EL (DEG)	AZ (DEG)	CT (NM)	ACQR (KFT)	POWER MARGIN	TT (SEC)
NOM	16.3	54	50	3.3	262.5	1.98	13.3
	16.3	54	47	3.1	247.4	2.23	12.0
	16.3	54	45	3.0	238.7	2.40	11.2
-2.5	13.8	58.4	50	3.0	249.4	2.20	12.7
+2.5	18.8	50.1	47	3.3	261.1	2.00	12.7

ASSUMES DH = 136.6 Kft., HALF FIELD-OF-VIEW (FOV) = 4° , STS SPEED = 15.8 Kft/SEC

TABLE I

IRIS:

3:53 PM TUE., 30 MAR., 1982

MILO'S ELEV = 65.96 TEL. ELEV = 31.06
CTE10 = -10.46
CT TOTAL = 10.69

1 EX Exit program
2 DH Difference in AC altitudes = 145783 23.98 mi
3 CTN Nominal Cross Track dist = 16.30
4 WPT Waypoint lats, lons = 30.47 -119.67 30.60 -118.27
5 CTE0 Cross track error (RADAR) = .80
6 CTI0 INS CTE at CTE0 time = -4.05
7 CTE71 SR71 cross track error = 0.00

8 TE Encounter Time (UT) = 15:51:12 TA=15:50:59
9 TDC De-Crab Time (UT) = 15:48: 0
10 TRT Tracking time (sec) = 13.00
12 WIND Expected wind at Acq. = -1 90 INS wind = 253 77
13 ELRA Max elevation rate (deg/m) = 3.50

IRIS:

TABLE 2

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IRIS

PROBABILITY OF SUCCESS

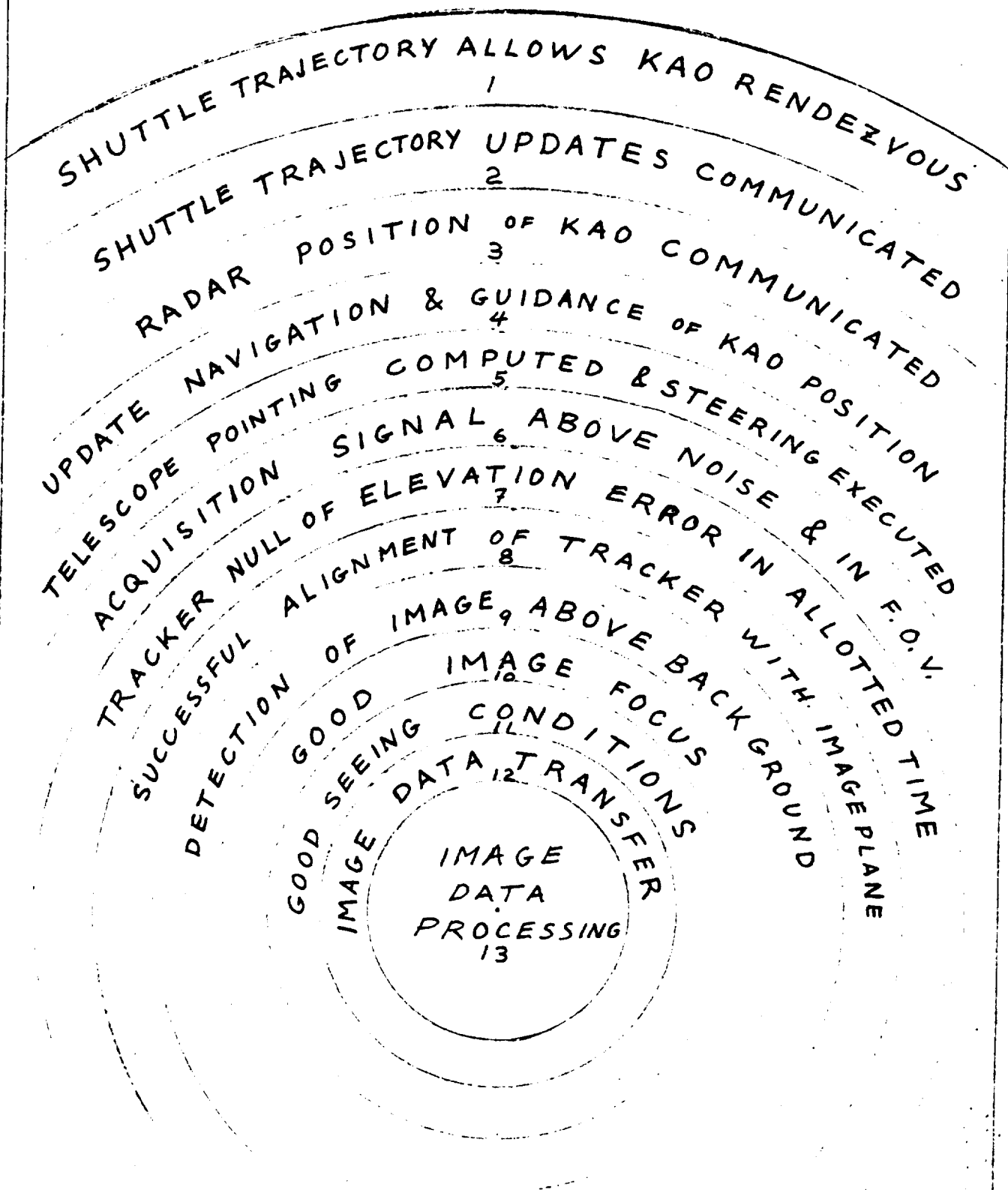


FIGURE 1

IRIS RENDEZVOUS GEOMETRY

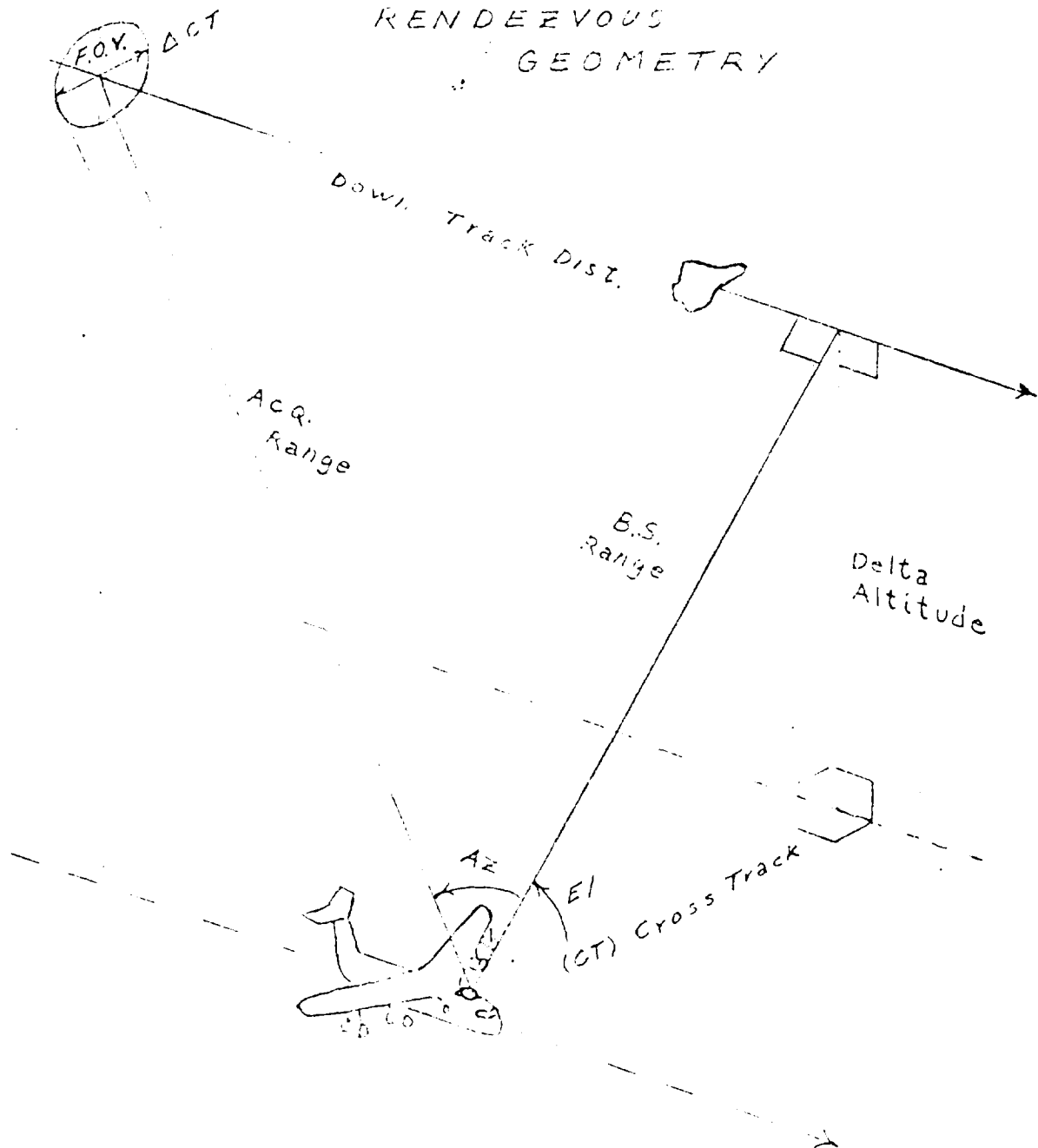


figure 2

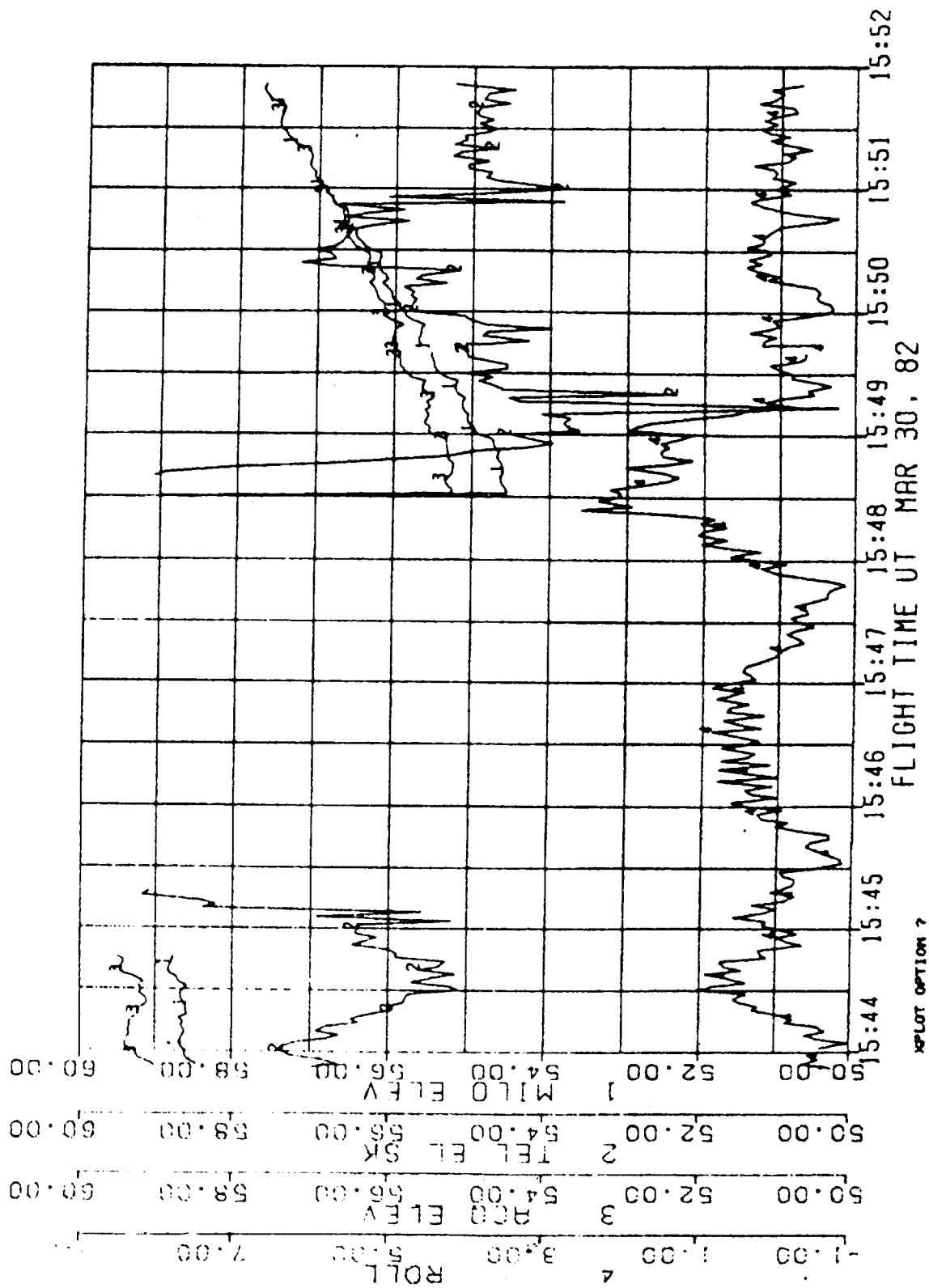


figure 3

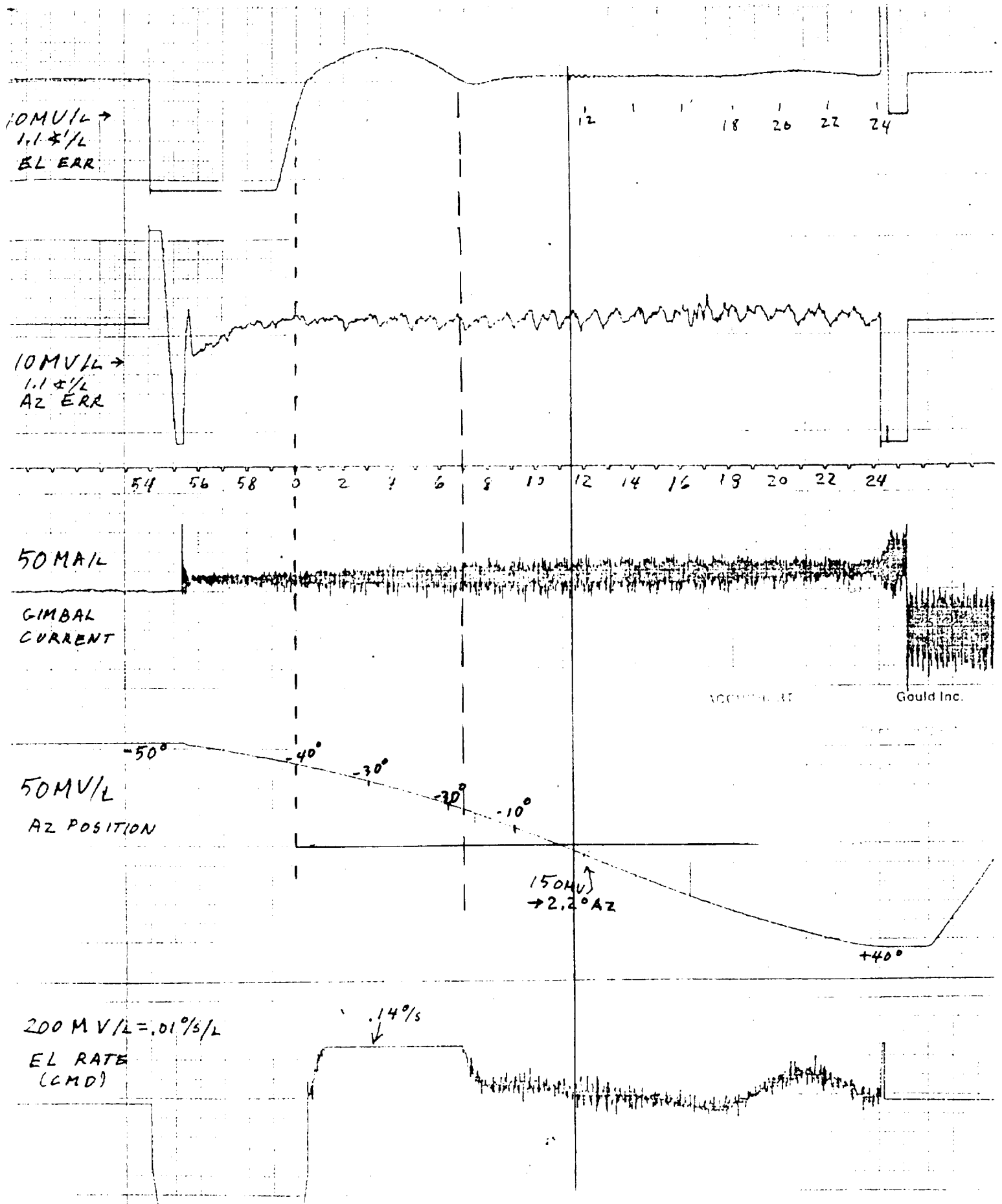


figure 4

IMAGE
DET

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APPENDIX 3.0

IRIS HARDWARE REPORT

Y. Matsumoto

3.1 Summary

The IRIS post STS-3 mission has revealed two significant problems: One which can be corrected, and the other which we may have to work around. The first problem is the misalignment between the IRIS tracker telescope and the Kuiper Airborne Observatory (KAO) telescope. This misalignment was the reason that we obtained only a partial image of STS-3. The second problem was the random occurrences of high noise levels on the IRIS tracker detector signal which could have prevented the acquisition of STS-3.

3.2 Details

3.2.1 Misalignment

The STS-3 image recorded by IRIS emphasizes how precisely the IRIS tracker telescope and the KAO telescope must be aligned for a successful mission. Fig. 1 illustrates where the STS-3 image passed over the IRIS detectors, partially missing the detectors. If the alignment was perfect, the image would have passed through the center of the detectors and a complete image would have been recorded. The alignment was checked after the STS-3 mission and was found to be misaligned by 3 arc minutes in the direction noted by the passage of the STS-3 image.

Fig. 2 illustrates what is meant by alignment. The IRIS tracker acquires the target and tracks the target in the horizontal (azimuth) and vertical (elevation) axis. The tracker moves independently of the KAO telescope in the azimuth axis but moves with the KAO telescope in the vertical axis. The IRIS tracker is designed to track a target by generating azimuth and elevation error signals for the control system. As the target moves past the KAO telescope, the elevation error signal would ideally be zero, and the image should pass through the center of the image plane. If the image does not pass through the center of the image plane, the IRIS tracker and KAO telescope are misaligned.

Fig. 3 illustrates how the alignment is performed. A collimated light source is used to produce the precise parallel rays of light that are required. The light rays were measured to be parallel to within 15 arc seconds over the region of interest. The alignment is performed by adjusting constants in the control system software such that the spot of light is centered on the image plane while IRIS is tracking the same light source.

Also illustrated in Fig. 3 is the light source that is used to check alignment during flight. The light source is rigidly mounted to the tracker and can be remotely turned off or on. The purpose for this

light is to detect any shift in the tracker mounting. The light ray tracing illustrates how the rays can be diverted by a beam diverter to deflect the rays onto the focal plane camera. The image of the light source is marked on a video display before a flight. The video screen is calibrated in arc minutes so that any shift during flight can be measured.

The misalignment that occurred may have happened because of a weakness in our testing procedures. The procedures were written so that the light source was adjusted while the collimator was installed. This was done to allow a quick check of the overall alignment after the light source had been adjusted. The adjustment of the light source is performed by shifting the position of its mounting, then tightening down on its mounting bolts. During the actual process of performing the work, it became evident that the light source could not be adjusted while the collimator was installed because of a lack of working space. It was then decided to adjust the light, being careful not to move the tracker, after the collimator had been permanently removed. This procedure had never caused a problem on previous flights.

3.2.2 Tracker Noise

The nominal noise level of the IRIS tracker detector is 50 mv peak to peak. During the testing of IRIS in preparation for STS-3, an additional noise source appeared. This sometimes resulted in a noise level over 250 mv peak to peak. This additional noise appeared as spikes superimposed onto the nominal noise level. This type of noise has appeared throughout the history of IRIS, but this was the first time that the durations and intensities had been so large.

It is generally believed that the noise is generated by the motor that is used to spin the reticle in the IRIS tracker telescope. This belief is based on the fact that the noise spikes disappear whenever the motor is turned off. The motor is a DC motor with brushes, and the brushes are suspected of being the source of the noise.

The manufacturer of the motor has been previously contacted about our problem and believe we are using the correct brushes for a low noise and low pressure application. He also believes that a basic error was made in using a motor with brushes for the IRIS application.

Unfortunately, a redesign to a brushless motor requires a significant amount of electronic redesign and testing. Also, we know of no brushless motor that would mechanically fit into our present design.

IRIS is able to operate under varying noise levels because of a design change that was added prior to STS-2. Fig. 4 illustrates how IRIS is able to operate in the presence of a high noise level signal. Threshold 1 can be viewed as a nominal threshold level that would be used for a nominal noise level situation. Threshold 2 can be viewed as the threshold level that would be used under a high noise level situation. The ability of IRIS to remotely control the threshold level has added immensely to its versatility. The advantage of being able to

vary the threshold is that the maximum sensitivity for given noise level can be obtained in real time.

3.3 Analysis of STS-3 IRIS Tracker Signal Strength

The signal level recorded at acquisition from the IRIS tracker was 1.4 volts peak to peak. This signal level was about 3.5 times as large as expected. It is crucial that this discrepancy be understood since the primary encounter point for STS-4 is at peak heating where the signal level is presently calculated to be marginal.

There are basically two sources of error that may have contributed to this discrepancy: Either the Shuttle was much hotter than previously assumed, and/or the laboratory test setup that was used to determine the preflight calculations is inaccurate.

STS-3 may have been much hotter than our preflight predictions. The predicted source strength for STS-3 was obtained from an extrapolation of STS-2 data as shown in Figure 5. The plot shows surface temperatures as a function of time after Entry Interface (EI) using the Development Flight Instrumentation (DFI) thermocouple located at $X/L = 0.3$ where X is the distance from the nose and L is the length of the Shuttle. Two area averaged temperatures (average temperature for all of Shuttle) were obtained for STS-2 using all 80 DFI thermocouples. These are also shown in Figure 1 at 9 minutes and at 19 minutes. Notice that they agree to within 10% of the plotted curve. Based on these comparisons, it was felt that the $X/L = 0.3$ data was a good indication of the area averaged temperature. As a cross check, the STS-3 DFI data (there is some concern for the exactness of this data as of this writing) was area averaged, and the results closely agreed with the $X/L = 0.3$ data. Using a calculated average temperature of 1020 K, it was estimated that the Shuttle radiated 4.1×10^6 watts in the 3 to 4 micron band of the tracker. Using the STS-3 DFI data, the radiated power was calculated to be 4.4×10^6 watts using an emissivity of 0.9. These results are close to the preflight calculations. Using the integrated source strength of 4.4×10^6 watts, the flux at the tracker is calculated as follows:

- o The altitude of STS-3 was 141,000 feet.
- o The boresight distance was 169,700 feet with the KAO telescope elevation at 55° .
- o The tracker look-back angle was 50° which resulted in an acquisition distance of 264,000 feet.

The flux density at the tracker aperture is then given by Lambert's law. Lambert's law states that the radiation normal to the radiating surface is equal to the total power radiated divided by π . Multiplying this value by the solid angle of the tracker aperture results in the power into the tracker. Since the view angle of the telescope was about normal to the radiating surface, no cosine term has been included.

$$\begin{aligned}
 \phi_{\text{TOTAL}} &= \frac{\text{TOTAL POWER}}{\pi} \times \frac{A_{\text{TRACKER}}}{(\text{DISTANCE})^2} \\
 &= \frac{4.4 \times 10^6 \text{ WATTS}}{\pi} \times \frac{\pi (1.1 \text{ in.})^2}{264,000 \text{ FT} \times 12 \text{ IN/FT}} \\
 &= 5.32 \times 10^{-7} \text{ WATTS}
 \end{aligned}$$

The preflight prediction was calculated to be as follows:

$$\text{Power} = \frac{E A_T W A_C J}{\pi R^2}$$

E = Emissivity, use 1 since W already contains the 0.9 factor.

A_T = Area of Shuttle, use $5.61 \times 10^5 \text{ in.}^2$.

$$W = \int_3^{\gamma} \frac{3.7415 \times 10^4 d\lambda}{\lambda^5 e^{(1.43889 \times 10^4 / \lambda T)} - 1}$$

λ = Wavelength

T = Degrees Kelvin

This equation is used to calculate the power in watts/in² radiating from a blackbody at a specific temperature in a specific wavelength range. Use 5.93 watts/in² as supplied by W. Davy.

A_C = Tracker telescope aperture area, use $(1.1 \text{ in})^2 = 3.8 \text{ in}^2$.

J = Transmissivity, use 1.

R = Distance from source, use $268,000 \text{ ft} \times 12 \text{ in/ft} = 3.216 \times 10^6 \text{ in.}$

$$\begin{aligned}
 \text{Power} &= \frac{1 \times 5.61 \times 10^5 \text{ in}^2 \times 5.93 \text{ watts/in}^2 \times 3.8 \text{ in}^2}{\pi \times (3.21 \times 10^6 \text{ in})^2} \\
 &= 4.32 \times 10^{-7} \text{ watts}
 \end{aligned}$$

The increase in power of STS-3 over predicted is:

$$\frac{5.32 \times 10^{-7}}{4.32 \times 10^{-7}} = 1.23 \text{ (FACTOR 1)}$$

Our preflight calculations could easily have been in error by 10%. This increase accounts for only a minor portion of the 3.5X increase observed.

The second source of error is the laboratory test setup that was used to determine the preflight calculations. The lab set consists of a blackbody source, three mirrors, and a collimating lens as illustrated in Figure 6. In order to eliminate as many sources of error as possible, a measurement of signal strength was made using only a blackbody source and the IRIS tracker as shown in Figure 7. The blackbody was adjusted to 700 K, and the aperture was set at 0.1 inch diameter. The power at the tracker was calculated using the following equation:

$$\text{Power} = \frac{E W A_c \tau \Omega}{\pi}$$

E = Emissivity, use 1 for blackbody.

τ = Transmissivity, use 1.

W = 1.272 watts/in² for a 700°K blackbody from 3 to 4 microns.

A_c = Tracker aperture area, use 3.8 in².

Ω = Solid angle subtended by the source.

$$= \frac{\text{Area of Blackbody aperture}}{(\text{Distance})^2}$$

$$= \frac{\pi (.05 \text{ in})^2}{(17.3 \text{ ft} \times 12 \text{ in/ft})^2}$$

$$= 1.82 \times 10^{-7} \text{ steradians.}$$

The power calculated by this method entering the telescope aperture was 2.8×10^{-7} watts which produced a pre-AGC voltage output of 0.8 volts peak to peak. The signal out of the detector is proportional to the power input, therefore, we can calculate the signal output for an input of 4×10^{-7} watts.

$$\frac{.8 \text{ V}}{2.8 \times 10^{-7} \text{ watts}} = \frac{V}{4 \times 10^{-7} \text{ watts}}$$

$$V = 0.8 \frac{4 \times 10^{-7}}{2.8 \times 10^{-7}} = 1.14 \text{ volts peak to peak}$$

Our present method indicates our signal output for an input of 4×10^{-7} watts is 1.14 volts. Our previous measurements using the lab test setup produced a signal of $0.4 \pm .020$ volts. The lab test setup was in error by a factor of

$$\frac{1.14}{0.4} = 2.85 \text{ (FACTOR 2)}$$

The combination of Factor 1 and Factor 2 times the expected signal of 0.4 volts should be approximately equal to the STS-3 signal at acquisition.

$$1.23 \times 2.85 = 3.5 \\ \text{(Factor 1)} \times \text{(Factor 2)}$$

$$3.5 \times (0.4 \text{ volts}) = 1.4 \text{ volts.}$$

The acquisition signal should have been 1.4 volts. The actual signal was approximately 1.4 volts at 0.4° from the edge of the field of view. The correlation between these numbers is striking; but even if they agreed within 20%, our argument would still be valid.

The question remains, why were the preflight calculations so much in error? The most probable source of error is the lab test setup which was used to calculate the preflight signal levels. The lab test setup had been delivered as part of the IRIS equipment. After considering different methods to test the lab setup, it was decided to do the following. The blackbody was adjusted to 1300 K so that it radiated in the visible range. This allowed visible ray tracing which simplified the measurement of the light bundle that reached the tracker. This approach allowed us to quickly determine that the bundle of radiation into the tracker had a cross-sectional diameter of 1.2 inches instead of the 2 inches we had used in our preflight calculations. The difference in radiant energy is directly proportional to the ratio of the areas.

$$\frac{\pi (1 \text{ in})^2}{\pi (0.6)^2} = 2.78$$

Number 2.78 compares favorably with Factor 2 with a value of 2.85. Although the 2.78 number has not been derived by checking all sources of error in the measurement, it is irrelevant since the most accurate way to determine the tracker sensitivity is by the method shown in Figure 3.

The results of the tests have led us to conclude that the tracker is approximately 2.85 times as sensitive as previously assumed. These results strengthen our position for an encounter at peak heating since our previous calculations indicated signal strength to be marginal.

3.4 Conclusions

3.4.1 Misalignment

If we are correct in our assumptions as previously discussed, a procedural change should correct this problem. The procedure will be changed so that the in-flight alignment light source is installed before the final system alignment. A verification of alignment will be made after the next SR71 test flight.

3.3.2 Motor Noise

It is felt that IRIS can be operated in its present configuration due to the following reasons:

- (a) The noise level since STS-3 has been nominal and the high noise level situation has not reappeared.
- (b) IRIS can operate satisfactorily under a varying noise level environment.
- (c) A motor change cannot be done in time for STS-4 and such a change would be a major undertaking.
- (d) A nitrogen purge line to the motor assembly has been shown during laboratory tests to be effective in motor noise reduction. This modification will be flight-tested during an SR-71 system test flight and will be retained if the evaluation results are satisfactory.

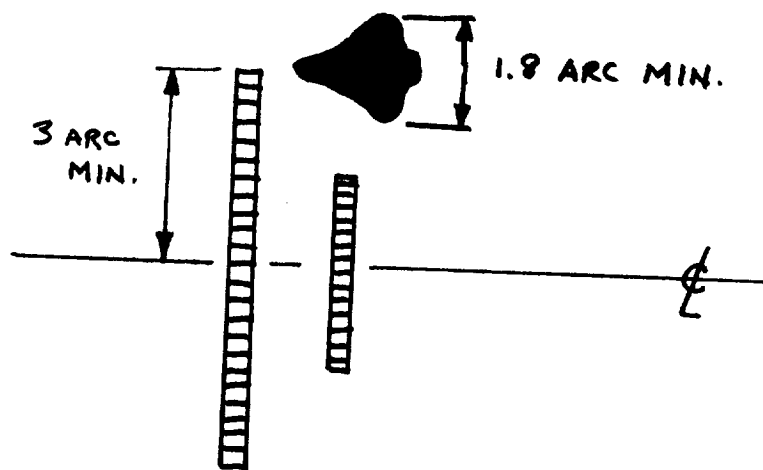


FIGURE 1

KAO TELESCOPE WITH

IRIS TRACKER AND IMAGE PLANE INSTALLED

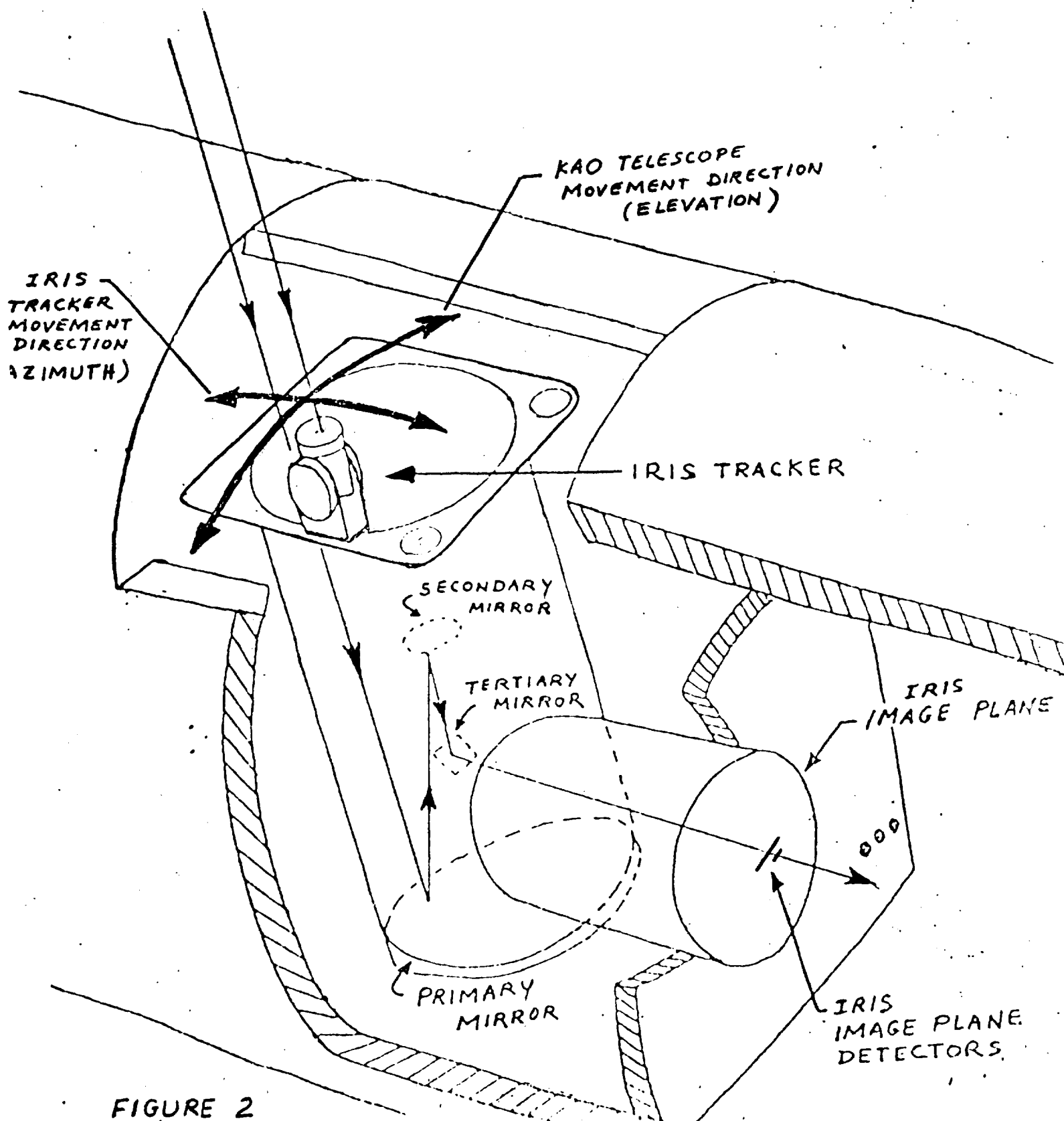


FIGURE 2

FINAL ALIGNMENT OF IRIS TRACKER TO KAO TELESCOPE USING A COLLIMATED LIGHT SOURCE

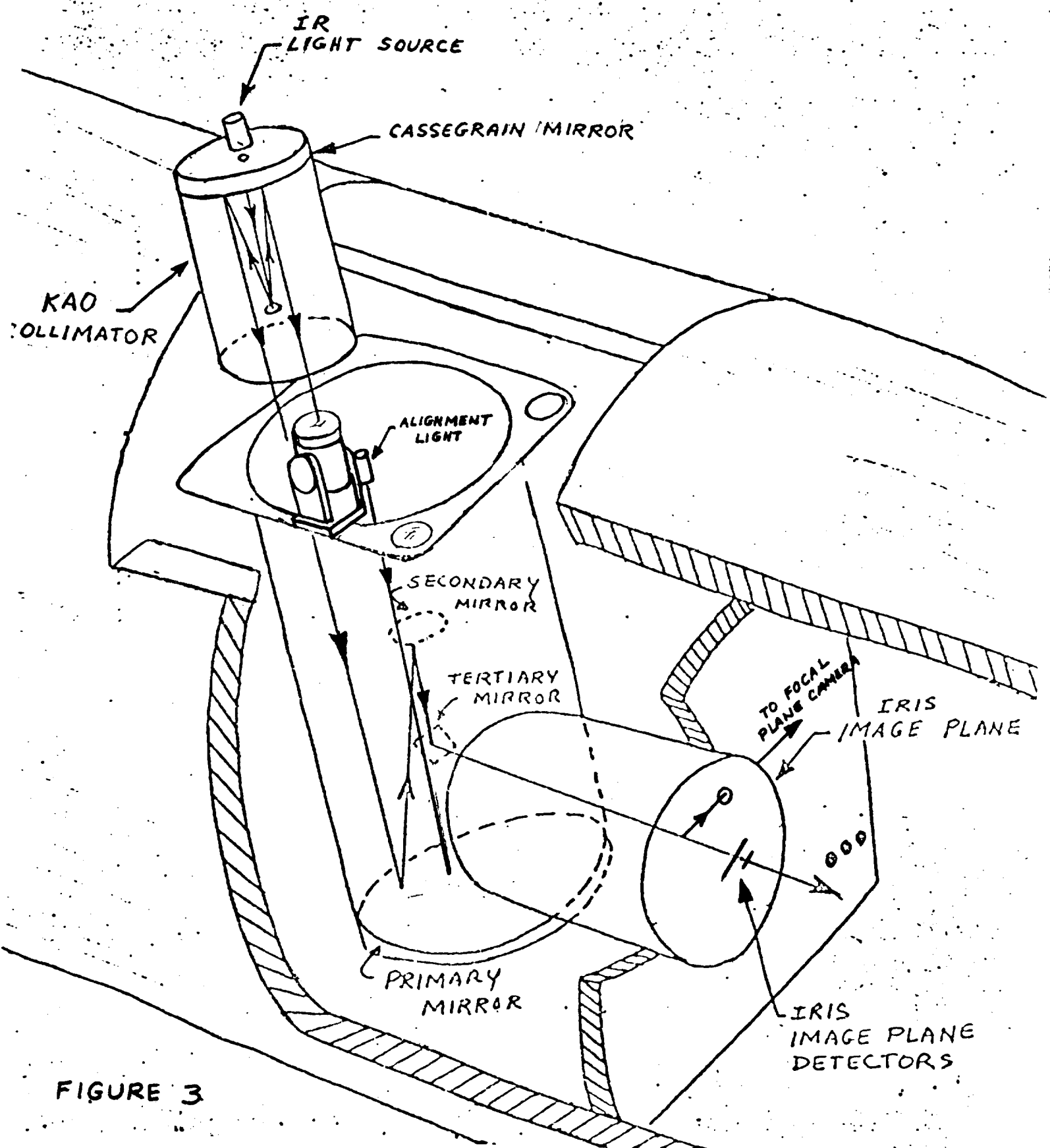
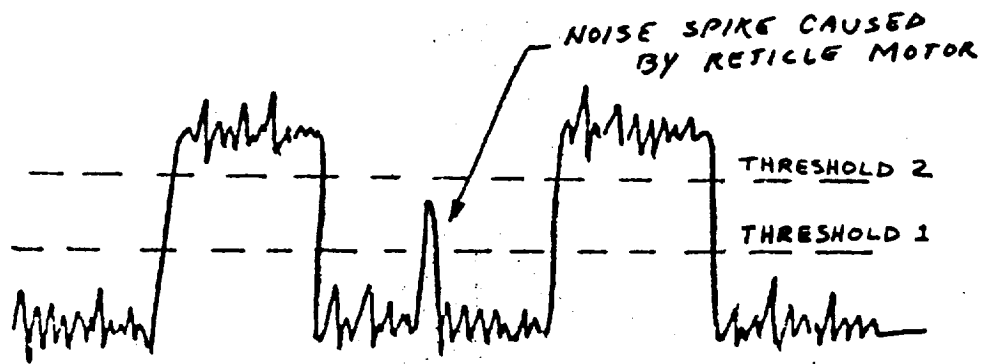
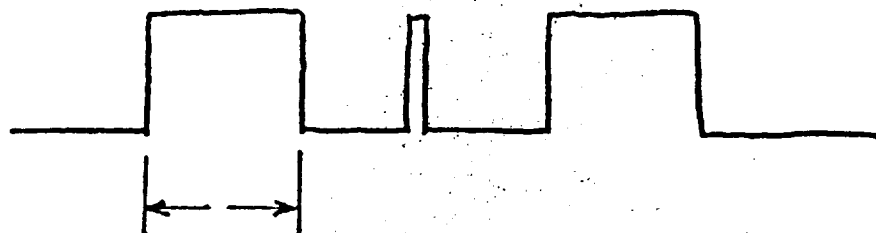


FIGURE 3

IRIS TRACKER
SIGNAL



DETECTION OF
SIGNAL



ERROR SIGNALS
ARE A FUNCTION
OF PULSE WIDTH

EFFECT OF NOISE SPIKES GENERATED
BY THE RETICLE MOTOR

FIGURE 4

STS 2 SURFACE TEMPERATURES

$$X/L = 0.3$$

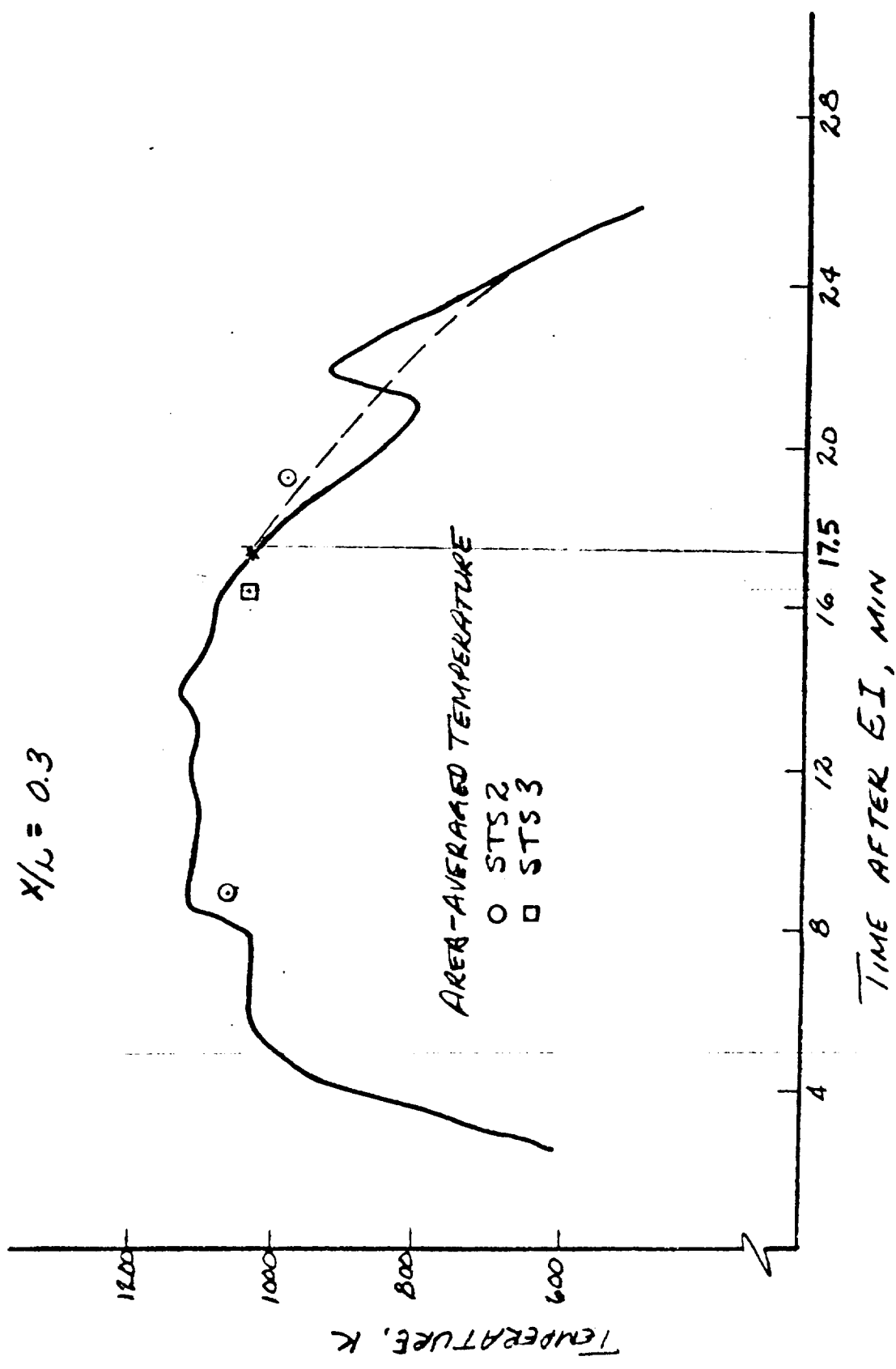
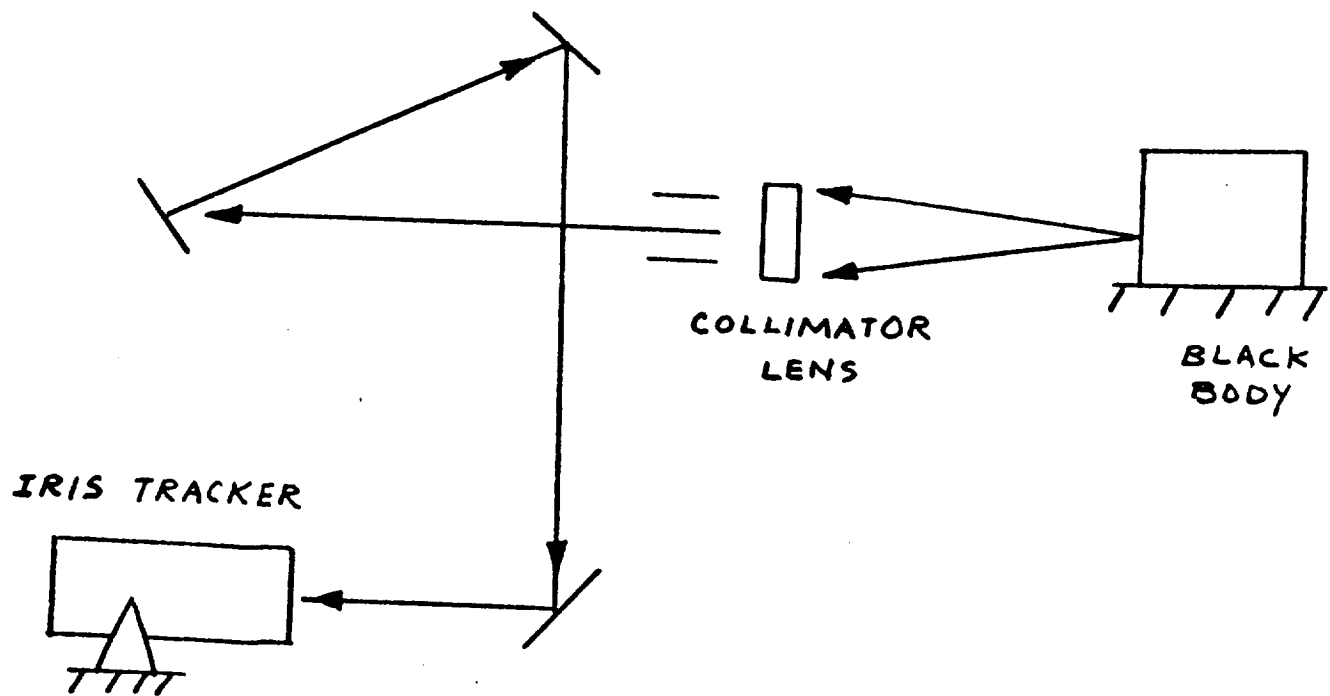
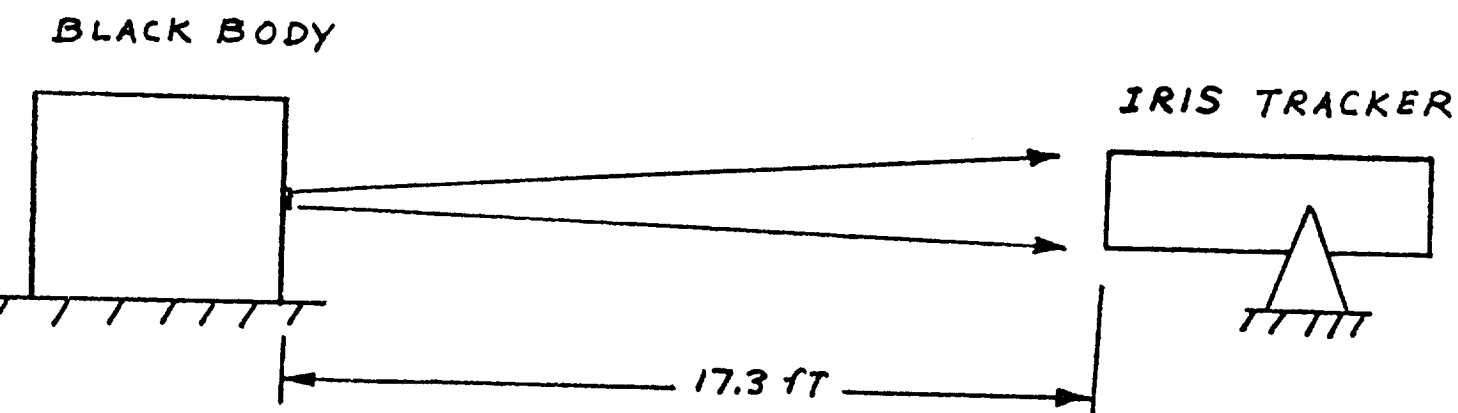


Figure 5



LAB TEST SET UP
FIGURE 6



SIMPLIFIED TEST SET UP
FIGURE 7

APPENDIX 4.0

IRIS SOFTWARE REPORT

B.J. Bar-Gadda

4.0 The IRIS Software

The IRIS Software is composed of many programs. These programs calibrate and diagnose the hardware, drive the tracker telescope, and reconstruct the recorded shuttle image. For an overview of the entire data acquisition and reconstruction process see Figures 4.0.1 and 4.0.2. The tracking and the reconstruction programs are discussed below.

4.1 The Tracking Software

There is a single program, TRAK, which controls the IRIS acquisition tracker. This program is approximately 3000 lines of code and is written in HP assembly language and in Fortran. The flow diagram for TRAK is given in Figure 4.1.1.

After the TRAK program is loaded, it prompts the operator for inputs. Some of these inputs must be experimentally derived every time the IRIS hardware is put on the KAO. One such input is the distance or bias between the null position of the IRIS tracker and the boresight of the IRIS image plane. Other inputs depend on the actual mission: the acquisition angle of the tracker for example. See Figure 4.1.1.a for listing of input parameters used for STS-3.

Once these inputs have been entered, the system waits until the operator tells it to point to the selected acquisition angle. During a mission the tracker is pointed 3 to 5 minutes prior to expected encounter time.

As the program begins to point the tracker it enters a loop. It reads its current angular position from the IRIS hardware position resolver. It then calculates the direction and the distance it needs to travel and sends the tracker on an appropriate rate signal.

During the loop the program queries the tracker to see if it has seen an IR signal. If an IR signal has been seen, the program waits for five consecutive signals before it will close the control loops. If no signals are seen the program continues to move the tracker to the acquisition position.

Once the tracker reaches the desired acquisition angle the program sends it a zero rate command. The program waits for the tracker to see a sequence of five continuous IR signals.

The tracker has an infrared detector. In front of the detector is a reticle which spins once every 33 ms. The tracker telescope focuses

the shuttle image as a small spot onto the reticle. The reticle opening has an epicyclic curve on one edge and a straight line on the other. The distance measured between two points on each side of the opening along the perimeter of a circle concentric to the reticle perimeter is equal to the length between either point and the center of the reticle. See Figure 4.1.2.

If the detector sees an infrared source it produces a voltage proportional to signal strength. When the spinning reticle covers the source the tracker voltages ceases. The duration of the tracker voltage measures the radius between the source and the center of the reticle.

An index pulse is produced once per revolution. The time measured between the index pulse and the cessation of the detector signal determines the angle between the index pulse position and infrared source. The hardware translates this position information into a polar coordinate system, returning to the program a radius and an angle theta. See Figure 4.1.3.

Unfortunately, given the above hardware constraints, noise in the system can be interpreted as a signal. Noise, therefore, has been a continuous source of false tracks and spurious outputs to the KAO telescope elevation control. Many of the software modifications to date have been implemented to neutralize the effect of noise on the system. See Figure 4.1.4.

The position information is fed into two control loops. The first uses the cosine of the angle and the radius to calculate the rate and the direction the tracker should move in azimuth. The second uses the sine of the angle and the radius to compute the movement of the KAO telescope in elevation.

Once the tracker begins to follow an IR signal the program can not be interrupted by the operator. The program can only be stopped by halting the CPU. When the IR signal has been lost, i.e. there have been 25 consecutive iterations with no IR signal, the program exits the track loop. The operator can now interact with the program.

4.2 The Reconstruction Software

There are currently three offline programs used to reconstruct the shuttle image. They are composed of approximately 2,000 lines of code and are written in Fortran.

The first, TSK6, adjusts the IRIS raw data counts for the variation in time sampling of the detectors. The second, TEM6, transforms the time corrected data into temperatures. And finally, PRT3, corrects for the physical offset between the odd and the even detectors in an array, rearranges the pieces of an image into a single contiguous image, and writes an ASCII tape of temperatures which can be read by other computers.

Each of these programs is described in the IRIS Software User's Manual Vol. 1. What follows is a summary and an update to that information.

4.2.1 Image Data Acquisition

Several minutes before data acquisition, a quiescent level and a channel gain are recorded on tape for each of the 200 channels. These records are obtained by running the program, CAL8 (first option 6, then option 4). They provide a snapshot of channel behavior just prior to encounter. They are used in the offline processing. Thus for the most accurate imaging results, these records should be taken under conditions as similar as possible to those of the encounter. See Figure 4.0.1.

There is no software involved in the writing of an image into IRIS memory: it is done by the hardware. The hardware continuously writes and rewrites memory. When a data level above the user selected summation threshold is sensed, it continues to write memory. This time, however, the hardware stops writing when the next memory address to be written is identical to that where threshold was first sensed.

There are two detector arrays, a 400 and a 200 element array. There are two sections of IRIS memory which contain 408 x 200 memory locations each. As the shuttle passes over one of the arrays it writes the first half of memory. When shuttle reaches the second array and threshold is again sensed, the second half of memory is written. Thus the direction of the shuttle determines which half of memory contains the data from the 400 or the 200 array. See Figure 4.2.2.

Since each detector has a unique responsivity it is necessary to know precisely which detectors wrote the image. Every three detectors are serviced by one single channel. For example, Detectors 1, 201, and 401 all use the identical channel, channel 96, to write data. During acquisition the distance between the two arrays is greater than the shuttle image length and the distance between detector 1 and 201 is larger than the shuttle image width. Thus the data written from channel 96 is taken from a unique detector.

There is only a one-to-one correspondence between a detector and its channel in the 200 element array. Consequently if both arrays see the shuttle image, the output from the 200 array is needed to determine which elements in the 400 array saw the shuttle. If, as in the STS-3 mission, only the 400 array sees the shuttle, the detectors which wrote the image can be determined from the hardware geometry.

Once IRIS memory has been written with an image, the program, TXFR, is used to transfer the entire 816 data records to a tape. Each record has 200 12 bit data words.

4.2.2 Reconstruction

The offline processing is a cumbersome process. Each half of memory must be processed separately. With each pass of the IRIS data, the programs write from tape to disk, disk to tape, etc. The overall flow is depicted in Fig. 4.0.2.

The IRIS experiment produces a 2-dimensional infrared picture of shuttle. The detector array provides one dimension of that picture. The second dimension is that of time: the detector array takes 408 snapshots of shuttle as it flies by.

Each snapshot of IRIS data, however, is collected over a period of 50 microseconds. TSK6 determines the relative sample time of each detector. It uses that information to rearrange the data between two sample periods to create a time adjusted record. In theory this record is identical to one in which all data had been collected simultaneously. An overview for TSK6 is shown in Figure 4.2.1.

There is a non-sequential relationship between a detector's physical position and the time at which it is sampled. Detector 1 is not sampled first, it is the 96th detector to be read. Furthermore the odd and the even detectors in an array are physically offset from each other by 2.7 detector lengths or 0.00675 in. Thus there is a time delay between the firing of the even and the odd detectors. (Figure 4.2.2).

A detector sample time information is derived from mapping the times at which the memory locations were written during data acquisition into channel sample times and finally into detector sample times. For example, the first five memory locations are written at time 0. These memory locations are written by channels 1, 41, 81, 121, 161. But those channels write the data from detectors 191, 111, 31, 50, and 130 respectively. Thus detectors 191, 111, 31, 50, and 130 were all sampled at time 0.

The time delay created by detector offset is corrected by adding 10 microseconds or .00675 in to the sampling time of the offset detectors. This "pushes" the offset array forward in time so that its data can be interpreted as being 3 complete detector lengths later in time than that of the non-offset subarray.

Once detector sampling times are known, a proportioning technique brings all detector data elements to the same time reference. Two consecutive data elements of a given detector, k , are averaged using the following formula:

$$\begin{aligned}\text{Prop1} &= \text{time}(k)/50 \text{ micro sec.} \\ \text{Prop2} &= 1.0 - \text{Prop1}\end{aligned}$$

$$\text{Data}(k) = \text{sample1}(k)*\text{Prop1} + \text{sample2}(k)*\text{Prop2}$$

The data is now corrected for time skew but not for shuttle speed. This correction must be applied later. Next the program, TEM6, converts it to temperatures. See Figure 4.2.3.

All of the detectors are Indium Antimonide detectors. The detectors in the 400 array are made from the same wafer, those in the 200 array from another. These detectors have similar and consistent responsivities. Thus if one detector is calibrated the temperatures of all other detectors can be determined by their relationship to the calibrated detector.

Detector 200 has been calibrated at 13 temperatures ranging from 600 to 1400 K. All other detectors have been calibrated at 1300 K. The counts for a given detector, k, are related to detector 200 by the following formula:

$$\text{det}(k) = \frac{\text{time adjusted cnts}(k)}{\text{realtime gain chan}(k)} * \frac{\text{cnts}(k) \text{ at } 1300 \text{ K}}{\text{cnts}(200) \text{ at } 1300 \text{ K}}$$

These corrected counts are interpolated between the 13 calibrated points of detector 200 to produce temperatures in degrees Kelvin. The program does not currently handle temperatures greater than 1400 K.

Finally, the IRIS image is disjoint spatially. As already noted, the odd and the even detectors of an array are physically offset from each other. This means that the odd rows of IRIS temperature data are offset from the even rows. In addition, the image can appear in fragments throughout IRIS memory. This is caused by the peculiar mapping between IRIS detector and IRIS data memory location and the unpredictable moment when the hardware is triggered and begins to write the IRIS image. These two problems are corrected in PRT6. The algorithm for PRT6 is given in Figure 4.2.4.

4.2.3 CONCLUSIONS

Since the capture of a partial STS-3 image, the reconstruction algorithms have come under careful scrutiny. The reconstructed shuttle image displayed cool leading and trailing edges. The transition between large temperature differentials was not as abrupt as expected. It appears that the reconstruction process contributed to both of these phenomena. Further the effect of shuttle velocity and emissivities had not been taken into account.

In light of the above, the time adjustment and the conversion of the raw data are being done as an independent process. Now post STS flight data will become an integral part of the reconstruction process. In addition the storage capabilities of a mainframe computer will be used to minimize errors introduced when adjusting the data for time skew.

Overview Data Acquisition and Image Reconstruction
Data Acquisition

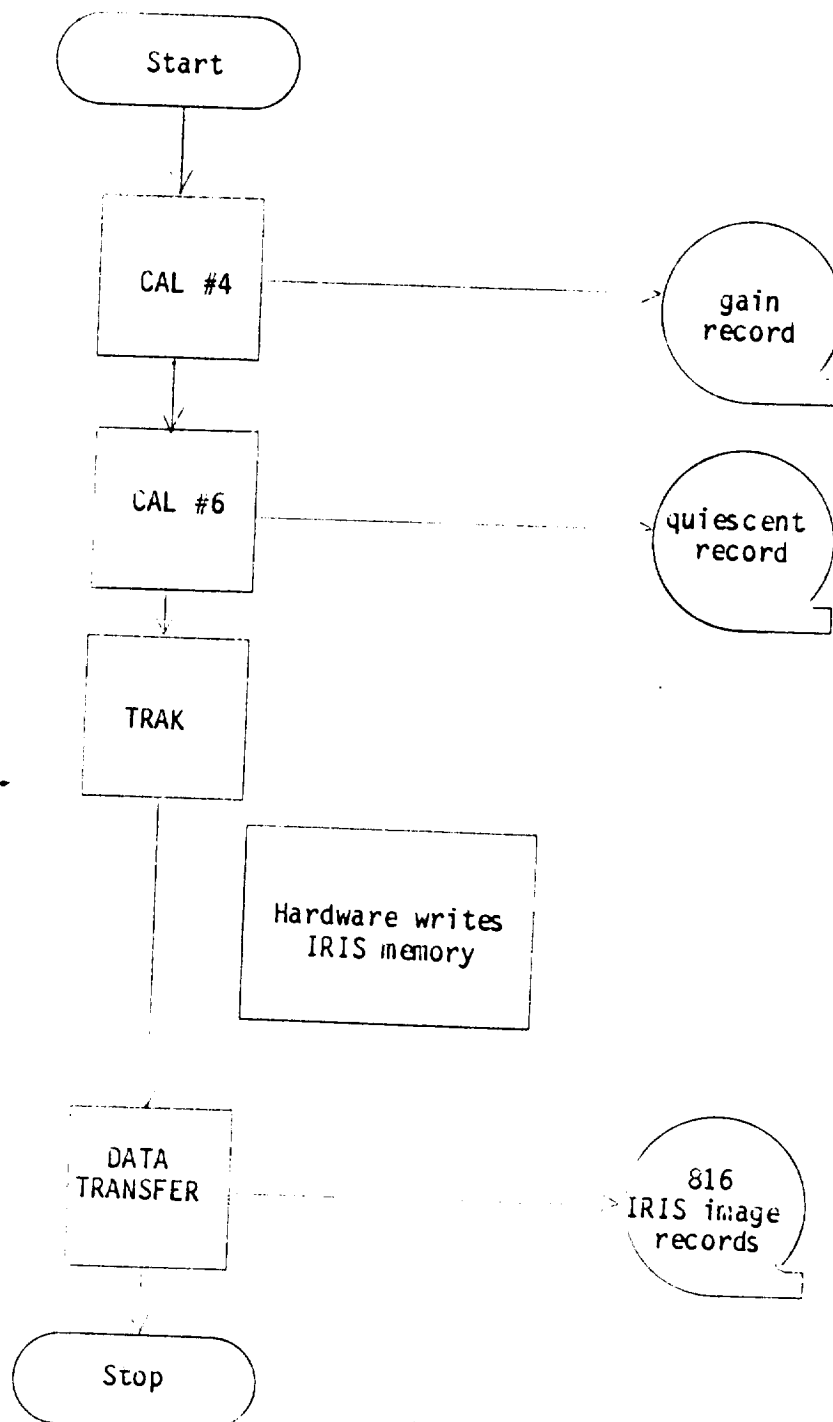


Figure 4.0.1

Overview Data Acquisition and Image Reconstruction
Image Reconstruction

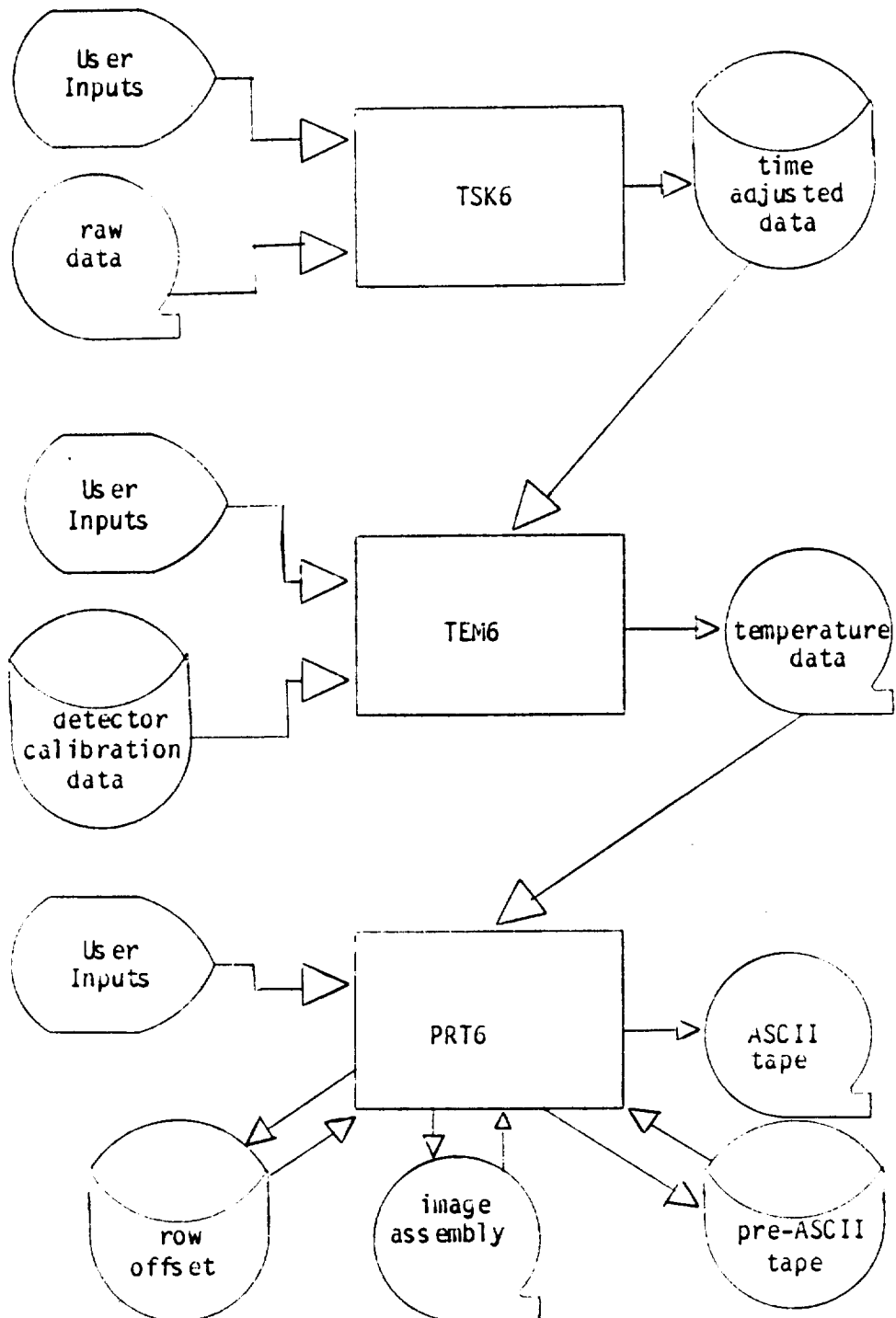
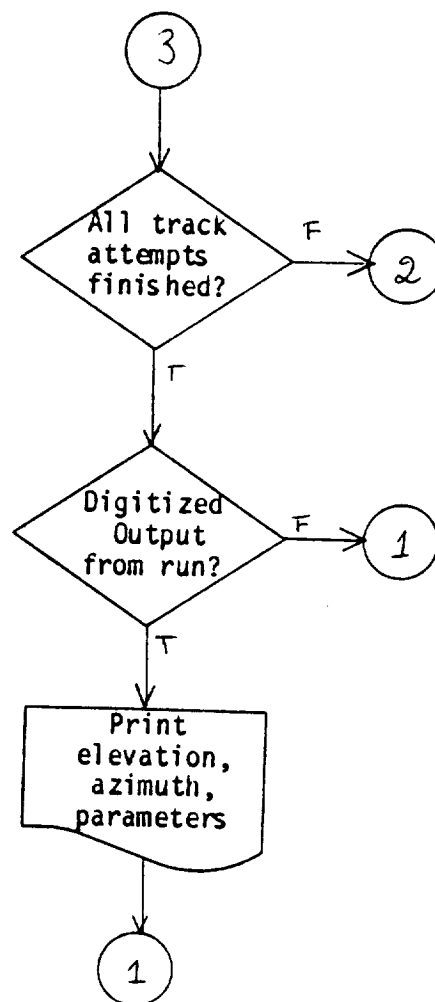
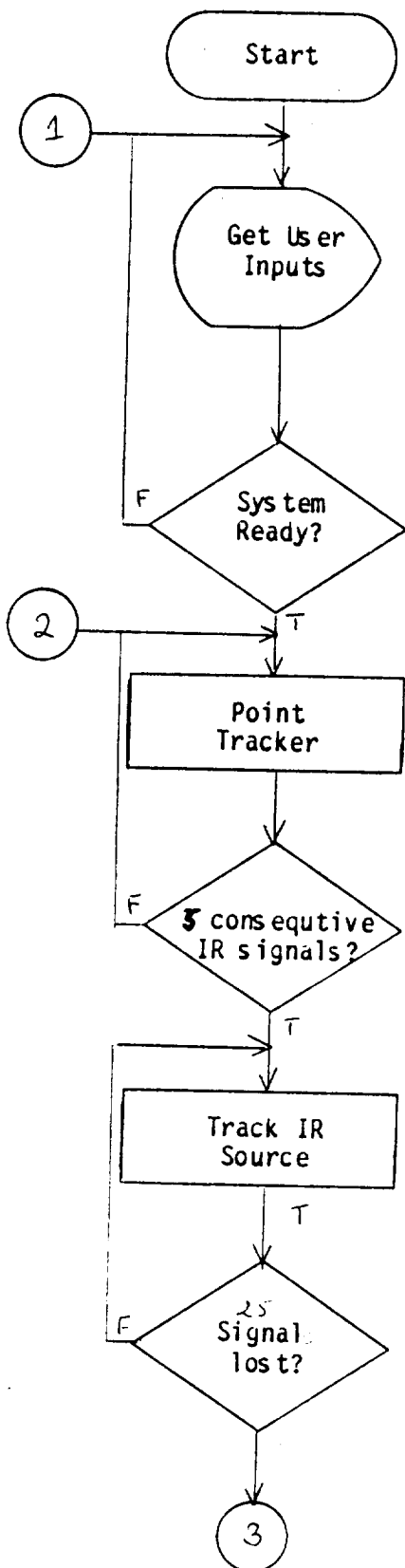


Figure 4.0.2



Flow Diagram of IRIS Tracking Software

Figure 4.1.1

```

.....DATA TRACE USER SUMMARY.....
TRACE IN ELTRK .....
ELTRK COEFF RE7, RE12 .....
NO. OF POINT LOOP INTERLUDES .....
NO. OF SAMPLES TO START, STOP TRACE .....
NUMBER OF TRACE ATTEMPTS .....
PHASE ROTATION ERROR (DEG) .....
NO. OF POINT, NO. OF TRACE ITERATIONS .....
AZTRK STEP DECLITCHER .....
BIAS IN AZTRK .....
AZTRK START RADIUS .....
AZTRK COEFFICIENTS AZX10, AZX11 .....
AZTRK COEFF RE1, RE6 .....
AZTRK COEFF AZX7, AZX8 .....
AZTRK RATE GAIN LIMITER .....
MAX RATE IN AZTRK .....
AZTRK DIRECTION LIMITER .....

```

CONTINUE ON TO NEXT SUMMARY (V-4)

```

.....DATA TRACE USER SUMMARY.....
BIAS IN ELTRK .....
ELTRK COEFF RE7, RE12 .....
ELTRK DECISION ANGLE .....
ELTRK INCREMENT .....
ELTRK DWP ANGLE .....
SPALL DWP ANGLE .....
ELTRK INTEGRAL CONSTANT RE1 .....
PROPORTIONAL HOLDING ANGLE (ANGLE) .....
ELTRK SPIKE DECLITCHER .....
ELTRK STEP DECLITCHER .....
MAX OF DROPOUTS ALLOWED PER .....
MAX OF SIGNALS .....
ELTRK RATE GAIN LIMITER .....
REAG OPTION IS ON .....
ERR SIGNAL CHAN 1: 0-CH04Z, 1-50 ENR0Z .....
ERR SIGNAL CHAN 2: 0-CH01Z, 1-50 ENR0Z .....

```

SYSTEM READY? (YES) OR (NO))

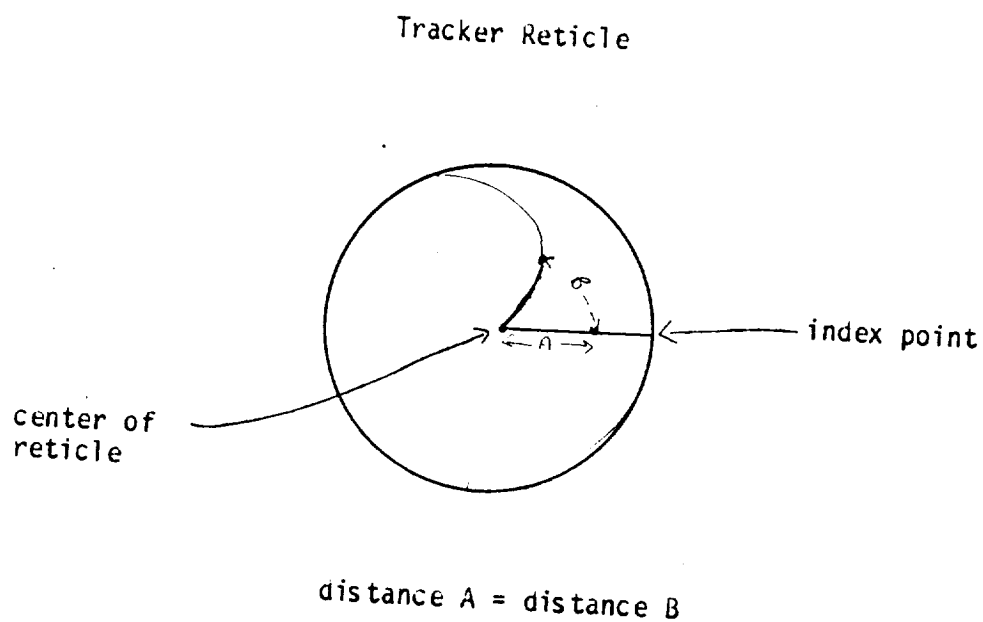


Figure 4.1.2

Tracker Position Information

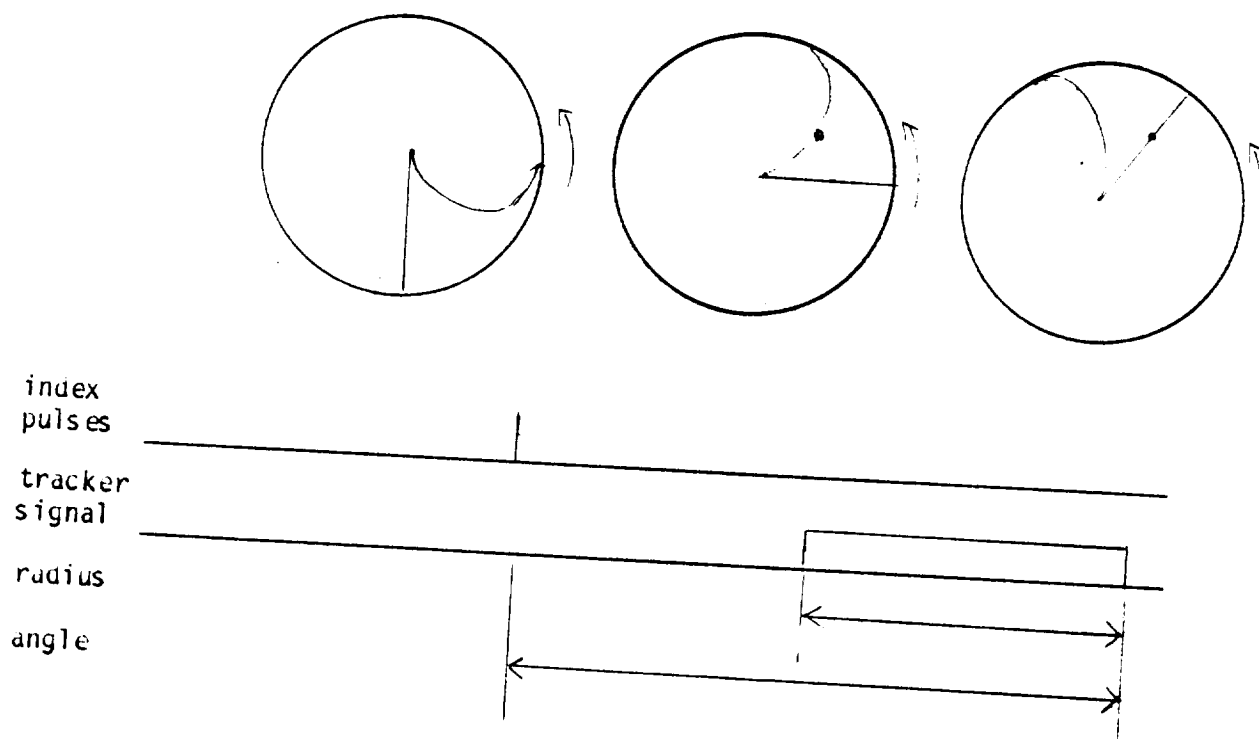
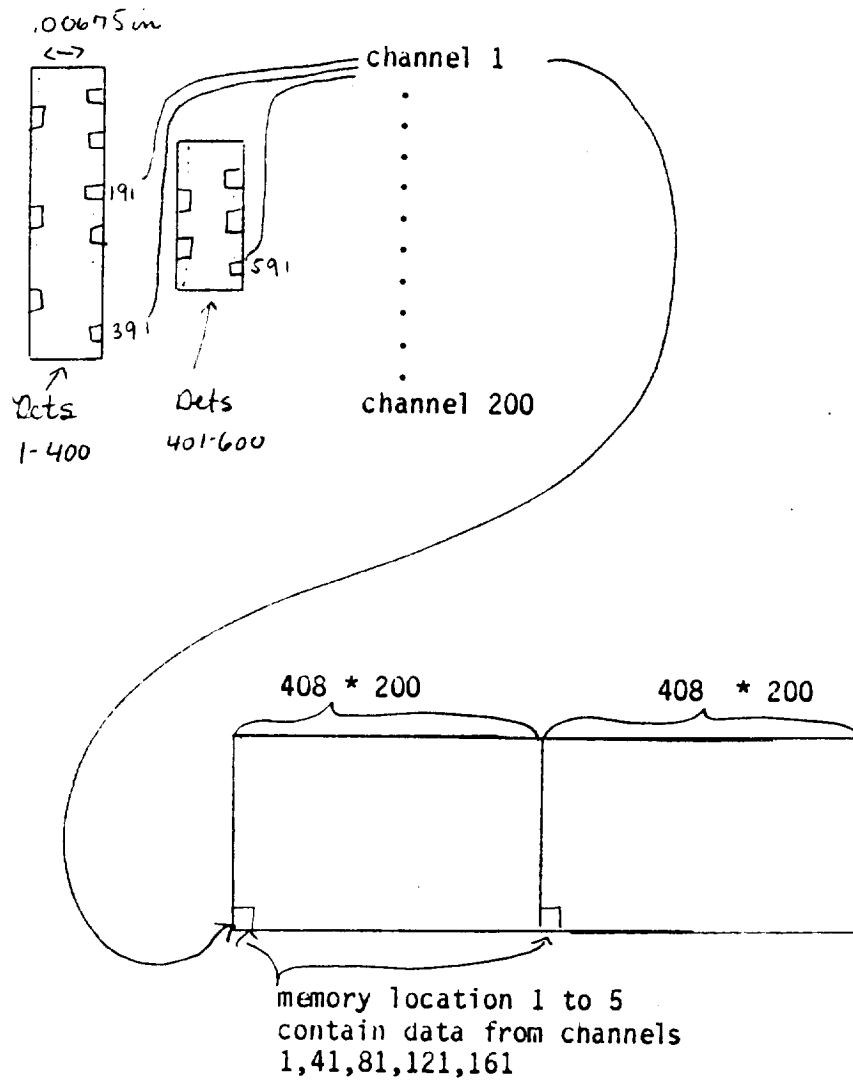


Figure 4.1.3

The Writing of IRIS Memory
Figure 4.2.2



IRIS Technical Changes - Software

October 19, 1981

I. Pre-Shuttle STS-1 Encounter

A. Tracking Software

1. Multiple track attempts and a variable input of number of signals to start and stop track.
2. Streamlining of input prompts for quick operator response.
3. Implementation of selection of some input constants as a function of tracker acquisition angle.
4. Restructuring of decisions in elevation loop.
5. The creation of a printerless version of track software.

B. Calibration Software

1. Addition of quick-look capability of IRIS memory.
2. The creation of a printerless version of calibration software.

C. Off-Line Reconstruction Software

1. The addition of variable logical unit inputs so that the software can be run on the C-141.
2. Ability to read gain and count records at the end of the image records.

II. Post-Shuttle STS-1/Pre-SR71 Encounter

A. Tracking Software

1. Corrected routine which checked timeouts between IRIS hardware and software and restructured calling code to count timeouts rather than halt the tracking software.
2. Added a subroutine which output the raw errors in azimuth and in elevation to the IRIS hardware so that they could be written in analog form to a stripchart recorder.
3. Implemented a smoothing function of the raw error in azimuth before it was put into the control system.
4. The software was modularized and restructured.
5. The ability to selectively use the printer was added.
6. The diurnal rate code was removed.
7. The ability to change the default constants and retain new values for all subsequent runs was implemented.
8. An integrator was added in the azimuth loop to allow the tracker to keep pace with an accelerating source.
9. The logic of the azimuth loop was altered to allow the tracker on initial acquisition to remain motionless until the source was well within the limits of its maximum "seeing" capability.

III. Post-SR71 Encounter

A. Tracking Software

1. New smoothing algorithm for input errors both in azimuth and elevation.
2. Ability to select two of the following errors for conversion to analog form to the stripchart recorder:

Raw error in azimuth, smoothed error in azimuth.
Raw error in elevation, smoothed error in elevation.
3. The prompting menu was split into two menus for easier readability.

IV. Pre-STIS-3

A. Tracking Software

1. Rewrite of elevation control, including ramp up and ramp down.
2. Made the phase rotation error constant an input variable.
3. A subroutine was added that determines if there are dropouts in the input radius. If there are 3 dropouts out of 15, a flag is set and no elevation rate is put out to the KAO telescope until the noise dropouts are less than 3 out of 15.

Algorithm for TSK6

```
Begin
Read the real time quiescents from tape;
Get user inputs;
Initialize the time averaging process by getting two
    records of raw IRIS in detector order;
Generate array of detector sample times;

While not all records are processed do
    Using sample times proportion the data from two
    consecutive detector samples;
    write the time corrected data to a disk file;
    get the next record of IRIS data in detector order;
end. (while)
```

Figure 4.2.1

Algorithm for TEM6

```
Begin
Read real time channel gains from tape;
Get detector counts from disk;
Determine which detectors wrote the data;

While not all records are processed do
    calculate total flux relative to detector 200;
    interpolate total flux into temperature;
end. (while)
```

Figure 4.2.3

The initial data reduction, however, will still be done on board the KAO. This includes sorting the raw data into detector order, calculating detector outputs in amps relative to detector 200, reassembling the image fragments and determining detector sample times. This data will then be converted to ASCII and written to tape. An additional calibration detector for the 200 array will be added.

This flight program will require at most two passes of the data, be menu driven, and will extract as much information as possible from the data itself. These changes should minimize operator intervention and cut the total process time from 1/2 to 1/3 what it is now. This program will be operational for STS-4.

Algorithm for PRT6

Begin

- Move odd rows forward or backwards a specified number of positions;
- Put vertical and horizontal pieces of image together;
- Dump image for a quick look;
- Write an ASCII tape of temperatures;

end.

Figure 4.2.4

APPENDIX 5.0

IRIS MISSION OPERATIONS REPORT

R. Lavond

5.0 MISSION OPERATIONS

The success of the IRIS Mission depended greatly on the efforts of many people besides those at Ames Research Center. For STS-3, IRIS Mission Control was set up at Dryden. This served as the focal point for gathering flight data, making real-time IRIS operational decisions, and providing them to the KAO. The Descent Flight Analysis Branch at Johnson Space Center (JSC) provided simulated descent ground track data that was used to initially plan the encounter point. The Flight Dynamics group at JSC provided updates to the simulated ground track data using real-time tracking information; PayDat/Shuttle Mission Control kept the JSC data groups aware of what IRIS' ever-changing real-time data requirements were, gathered the data and relayed it to IRIS Mission Control at Dryden Flight Research Center. The NASCOM network through Goddard Space Flight Center provided communication between the Centers and to Andrews Air Force Base for communications to the Kuiper Airborne Observatory (KAO) via the Air Force worldwide communication network (Fig. 1).

The IRIS mission support for the nominal STS-3 mission was conducted as planned. The Shuttle was to land at the Northrop strip in New Mexico on landing revolution 116. The KAO was positioned near Los Angeles on a parallel line south of the flight path of the Shuttle at the encounter point (Entry Interface (EI) + 17.5 minutes). Because of the limited crosstrack error allowable of only 2-1/2 nautical miles for both the Shuttle and the KAO, radar coverage from Vandenberg Air Force Base was being provided (Fig. 2) for both the KAO and the STS-3 to aid in vectoring the KAO within range of the Shuttle.

At approximately EI minus 45 minutes, the landing was aborted because of high winds at the landing site. The landing was rescheduled for the next day - either landing revolution 130 into Northrop which was prime, or 131 into Kennedy Space Center as an alternate. This caused a considerable amount of last-minute changes to the planned mission support. Instead of an encounter southeast of Los Angeles at EI plus 17.5 minutes, the encounter point for revolution 130 had to be moved to EI plus 16.5 minutes to keep the point over international waters off the Mexican coast of Baja (Fig. 2). The alternate encounter point (transitional flow) for revolution 131 into KSC was over Louisiana. This was not considered a viable alternative due to its distance from the prime encounter point. The peak heating encounter point for revolution 131 occurred over San Francisco and would have been a viable alternative except that it fell outside the allowable sun angle window of 55° from the sun to the telescope look axis.

Because of the changes of the reentry ground track, the radar tracking coverage provided by Vandenberg AFB had to be repositioned. High resolution boxes (4000 yds/inch resolution) had to be relocated for both the KAO and the Shuttle (Fig. 2). With the short time available, it was only possible to reposition the KAO high resolution box. Because of this, only the KAO position was known in real time and therefore only the Inertial Navigation System errors from the KAO were compensated for. IRIS relied on predictions from tracking data for determining the position of the Shuttle.

Once it was decided by Mission Control at JSC to land on revolution 130 at Northrop, JSC provided IRIS with simulated entry ground track data at about EI minus 14 hours. Updated data was provided at approximately EI minus 1-1/2 hours and EI minus 10 minutes.

The ground track of the Shuttle was determined by predictions from real-time trajectory data with the Aurora tracking station data as the final update at approximately EI minus 10 minutes. This information along with the radar position information was transmitted to the KAO where last minute adjustments were made to the airplane and telescope. Had high resolution radar been available for tracking the Shuttle, any deviation of the flight path from the Aurora prediction could have also been compensated for by changing the elevation of the telescope mounted in the KAO, increasing the probability of success. This was not necessary since the astronauts flew a real-time descent ground track very nearly identical to the predicted ground track in spite of roll position changes due to a descent on orbit 130 instead of 116.

The simulated ground track, the updates and the Best Estimated Trajectory (BET) position of the encounter point are shown in Fig. 3. This clearly shows that the Shuttle position updates are vital to the success of the mission since the allowable crosstrack error was approximately 2.5 nautical miles. The actual crosstrack error between the Shuttle and the KAO was 1.74 nautical miles.

IRIS/STS-3 was nearly a complete success. Approximately sixty percent of the underside of the Shuttle including all of the underside of the right wing were imaged. The Shuttle image projected onto the detector array appears in Fig. 4. Represented is the bottom of the Shuttle's right wing. The Shuttle longitudinal axis makes an angle of 3.9° with the telescope azimuth axis. Since the bottom surface of the Shuttle is not parallel to the image plane, lines originally perpendicular to the longitudinal axis and in a plane parallel to the Shuttle bottom appear skewed at 95.8° .

The information transfer between JSC and Dryden, between Dryden and the KAO, and between Vandenberg and the KAO worked very satisfactorily. No changes in concept will be made for future missions.

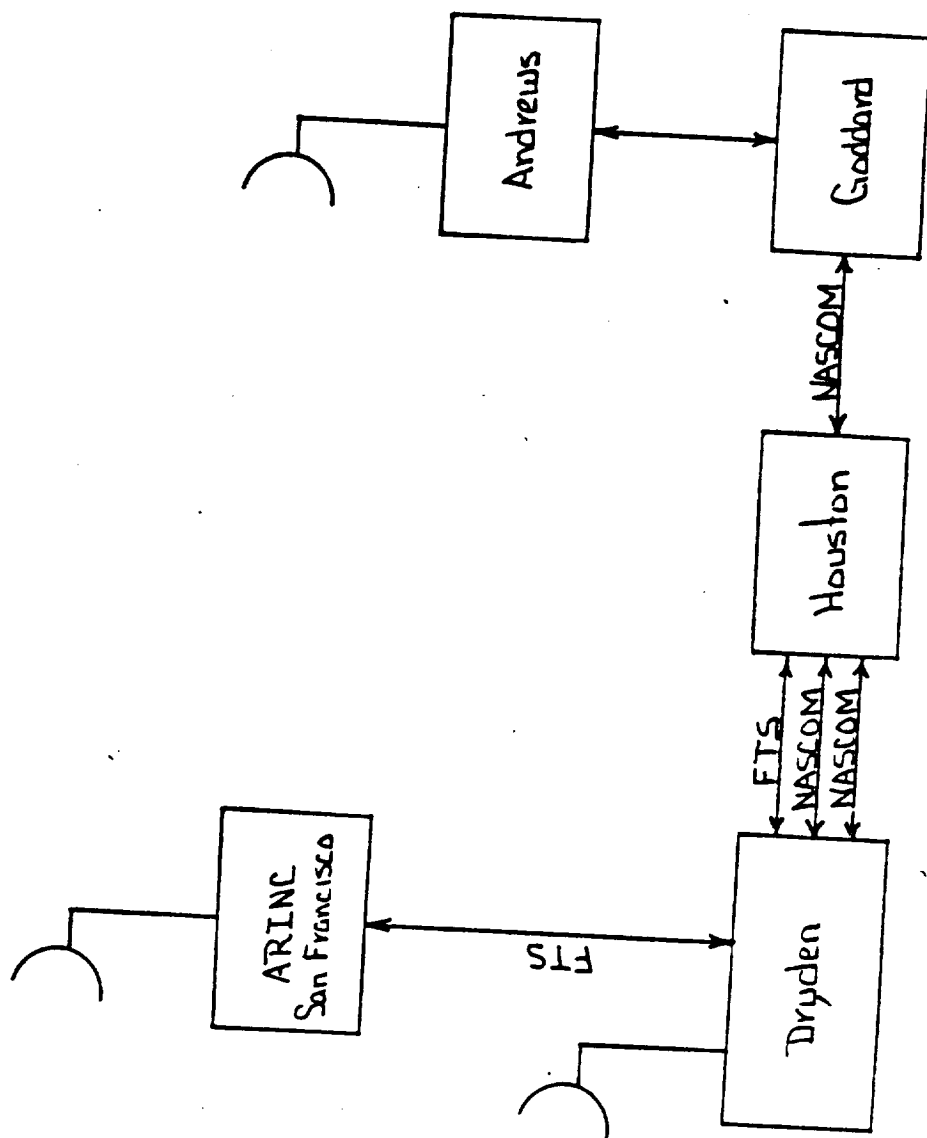


Figure 1



STS-3 INTO NORTHROP

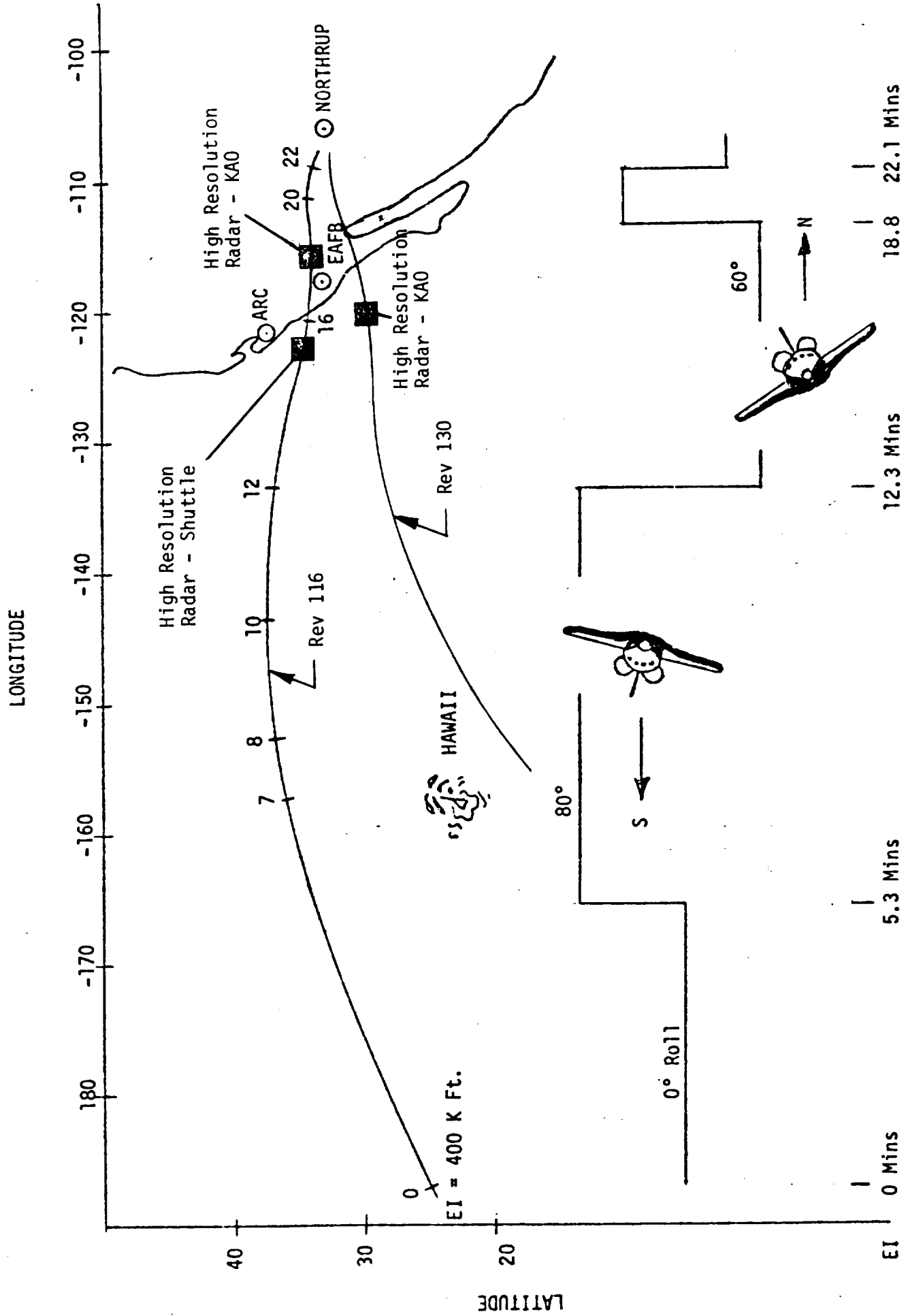


Figure 2

PREDICTIONS OF STS-3 LOCATION AT EI + 16.5 MINUTES

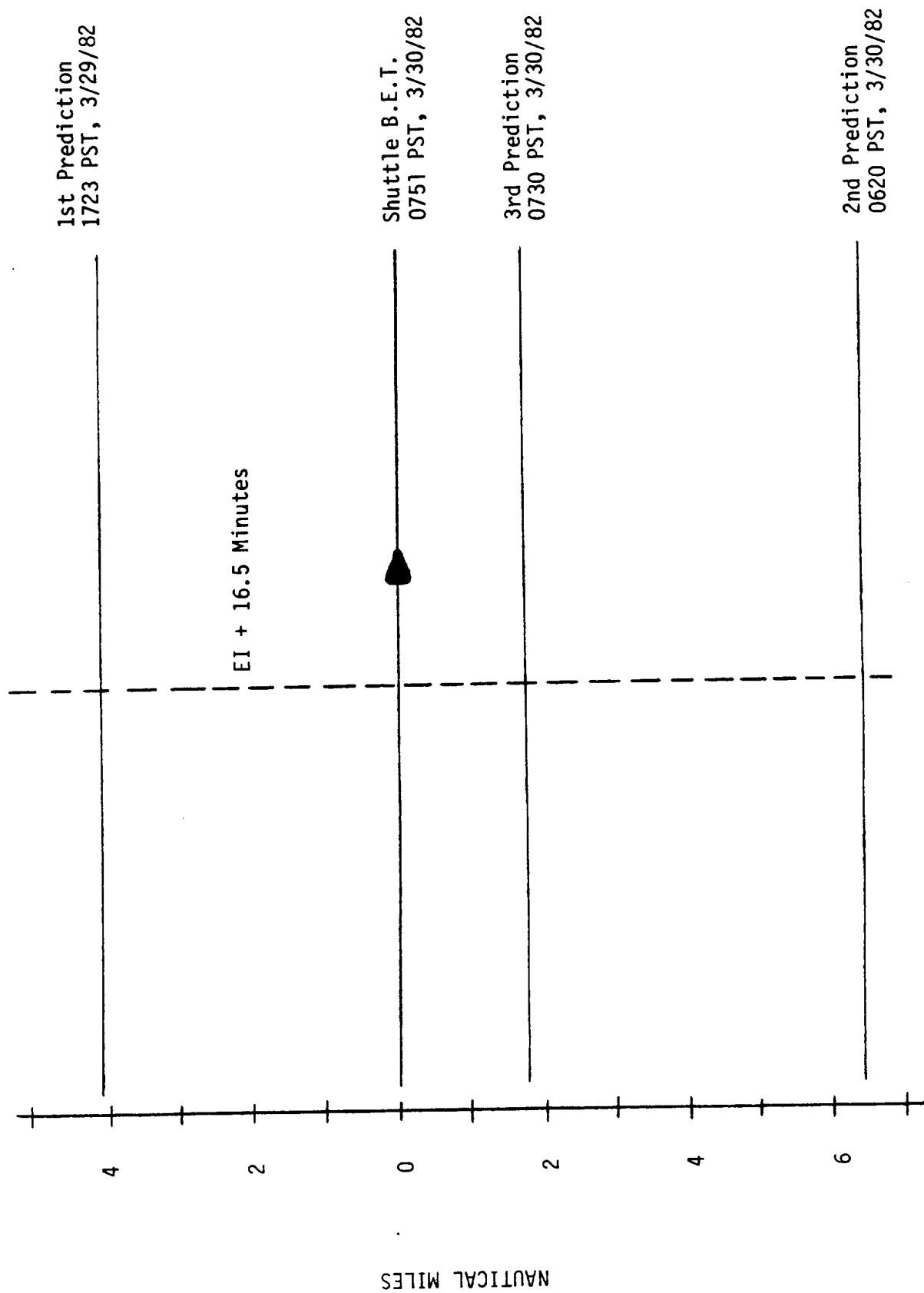


Figure 3

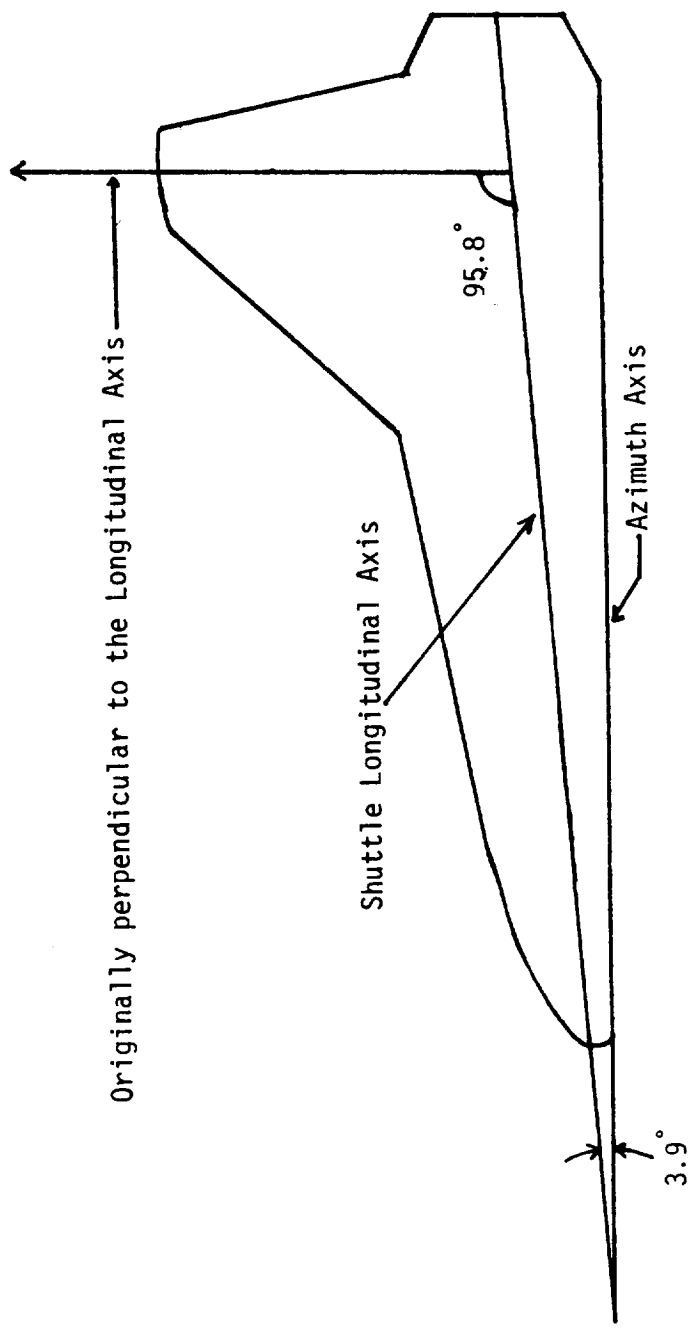


Figure 4

STS-4 INTO EDWARDS AFB (LANDING REV 112)

LONGITUDE

170 180 -170 -160 -150 -140 -130 -120

40

30

20

10

High Resolution Radar - KAO

HAWAII

Prime Encounter

S

N

0
EI=400 K Ft.

0° Roll

EI= 0 Mins

4.7 Mins

14.5

18.4 21.4 Mins

Figure 5

PROJECT MANAGEMENT STAFF

Project Manager
H. Lum

Principal Investigator: W. Davy

System Engineer: T. Grant

KAO Consultant: E. Erickson

Administrative Assistant: L. Hoffman

Experiment Team

Mgr: Y. Matsumoto
ARC

KAO Mission Team

Mgr: L. Haughney
ARC

Mission Support

Mgr: R. Lavond
ARC
JSC
DFRC
GSFC
Andrews AFB
Vandenburg AFB

Astronauts

J. Lousma
C. Fullerton
JSC

APPENDIX 6.0

IRIS/KAO OPERATIONS REPORT

L. Haughney

6.0 KAO OPERATIONS

6.1 SUMMARY

The NASA C-141 Kuiper Airborne Observatory (KAO) was the platform used by the IRIS Experiment to obtain an infrared image of STS-3 during its reentry on March 31, 1982. The KAO consists of a 91.5 cm telescope mounted open port in a Lockheed C-141A type aircraft (NASA 714), which is based at the NASA Ames Research Center under the management of the Medium Altitude Missions Branch and the Flight Operations Division.

The IRIS Experiment, installed on the KAO telescope, consists of three principal parts: an acquisition-tracking device mounted on the head ring of the telescope; a computer which processes the data from the IRIS tracker and then interfaces with the KAO computers and telescope; and an array of infrared detectors at the telescope's focal plane.

The Shuttle Orbiter and the C-141/KAO flew on parallel paths, about 16 nautical miles apart. The Shuttle overtook the airplane from behind. The IRIS tracker acquired the Shuttle at a range of 264,000 ft. and then followed it as it overtook and passed abeam of the telescope, which looks out perpendicularly to the left of the airplane. The IRIS and KAO data processing systems then translated the IRIS tracker's data into signals to move the telescope to the proper elevation angle to observe the Shuttle as the latter passed abeam of the airplane. The time between initial acquisition and passage through the telescope's field of view was only 16 seconds.

The accomplishment of the mission required precise navigation and timing, accurate, real-time knowledge of the aircraft and the Shuttle's positions, and skilled, experienced, and coordinated teamwork among all staff members. Three practice flights with a high-altitude, supersonic USAF SR-71 in late February and late March helped sharpen the skills, the working out of procedures, and the teamwork needed for the Shuttle flight.

Although the C-141/KAO was in the right place at the right time for STS-1 and STS-3, the experiences with all three Shuttle flights and with the SR-71 flights show that improvements in procedures systems can be made and that some of the KAO systems are only marginally adequate for IRIS needs. These areas of potential improvement involve: (1) better definition of duties and responsibilities of C-141 flight crews and KAO managers; (2) communication of navigational updates; (3) treatment of the navigational updates; (4) aircraft's navigational system; and (5) aircraft's autopilot.

6.2 CONCLUSIONS

The C-141/KA0 was in the correct place at the right time for STS-1 and STS-3. On the first Shuttle flight, STS-1, the Shuttle was acquired by the IRIS tracker and passed through the KAO's acquisition camera's wide field of view, which is boresighted with the 91.5 cm telescope. However, other systems' problems prevented the main telescope being moved to the proper elevation angle for a Shuttle image in its focal plane. STS-2 was about 25 miles off course because of manual maneuvers by the astronaut-pilots, and thus exceeded the IRIS FOV for acquisition. STS-3 passed through the KAO's focal plane's field of view, but somewhat off center so that an image of only 60% of the Shuttle was obtained. Despite these successes in navigating and flying the airplane, these experiences with the Shuttle and the SR-71 flights have shown that some C-141's systems and capabilities are being exercised near their limits.

6.3 RECORD OF C-141/KA0 FLIGHTS FOR STS-3

A detailed chronology of the C-141/KA0 flights made in support of the STS-3/KA0 project is given in the following table. Both the SR-71 flights and the STS-3 flights are listed.

The map (Figure 1) shows the actual C-141 flight track for the STS-3 flight on March 31, 1982. This map is plotted by the on-board data processing system (ADAMS) from the inertial navigation system data. It is evident from the map how the track of the airplane was shifted about five miles north of the track used for the practice run, due to the Shuttle trajectory update resulting from the de-orbit burn. That update was received at about T-20 minutes while we were returning to the start point after the practice run. High-resolution (± 0.2 nautical mile) tracking of the C-141 along the encounter track was provided by the Western Test Range Vandenberg AFB radar unit on San Nicolas Island, 160 nautical miles north of the aircraft.

Valuable real-time support of the SR-71 flights and the STS-3 flights was provided by the following agencies: Ninth Strategic Reconnaissance Wing, Beale Air Force Base, California, and the 2762nd Logistics Squadron of the Air Force Logistics Command, Palmdale, California, for the SR-71 aircraft; the Western Test Range, Vandenberg Air Force Base, California and the U. S. Army Electronics Proving Ground, Fort Huachuca, Arizona, for the radar tracking; and the USAF 2045th Communications Group, Andrews Air Force Base, Maryland, for the high-frequency radio communications.

IRIS/C-141 KAO FLIGHTS FOR STS-3 REENTRY

<u>Date</u>	<u>Take-Off Landing (PST)</u>	<u>Air Time</u>	<u>Purpose Area</u>	<u>Results</u>
2/25/82	-	-	SR-71 (Beale) encounter in Vandenberg/WTR Radar Range.	C-141 flight aborted. Line-of-sight gyro failure.
2/26/82	08:10 13:41	5h+31m	SR-71 (Beale) encounter in Ft. Huachuca Radar Range.	C-141 and SR-71 airborne on schedule. SR-71 aborted before reaching Ft. Huachuca. C-141 made two runs through radar range; practiced response to radar tracking, decrab maneuvers, HF communications networks. IRIS tracker affected by noise glitch at time of "simulated" encounter. KAO telescope unable to focus on daytime star.
3/23/82	10:18 15:28	5h+10m	SR-71 (Palmdale) encounter in Ft. Huachuca Radar Range.	SR-71 take-off delayed two hours. One encounter, both A/C W → E. IRIS tracker acquired SR-71, could not lock on because of weak IR signal. SR-71 not at peak heating. Radar tracking, C-141 track corrections, HF communications, all tested OK. Unable to find daytime star.

3/24/82	09:54 14:30	4h+36m	SR-71 (Beale) Encounter in Vandenberg/WTR Radar.	SR-71 take-off delayed two hours.
				Palmdale SR-71 and Ft. Huachuca radar up and ready to support.
				1st encounter, both A/C NW→ SE, missed SR-71, misinterpretation of timing update.
				2nd encounter, A/C opposite directions, <u>successful</u> <u>tracking of SR-71</u> by IRIS tracker from forward to aft; 1st complete airborne test.
				No focal plane image.
				Elevation drive rate slowed down too soon; strong cross-wind drifted A/C.
3/29/82	08:45 12:06	3h+21m	<p>STS-3 Reentry.</p> <p>Expected encounter at 19:14:30 UT.</p> <p>C-141: 35°54.5'N, 117°41.6'W, 41,000 ft.</p> <p>STS-3: 34°10.7'N, 116°24.4'W, 177,203 ft, 89.12° true heading.</p> <p>Cross-track separation = 16.3 n.m.</p> <p>Elevation angle = 54.0°.</p> <p>15 min. run between Los Angeles and Thermal, CA.</p> <p>Radar tracking of both C-141 and STS-3 to be provided by Vandenberg/WTR.</p>	<p>STS-3 landing delayed 24 hours after C-141 was airborne.</p> <p>Made two practice runs along encounter track to test all procedures. Radar tracking, communications, aircraft maneuvers, telescope operation.</p> <p>Successful focusing of telescope on Venus and Altair.</p> <p>Prior to announcement of delay, one update in orbiter track received.</p> <p>All systems OK.</p>

3/30/82 05:50
09:18

3h+28m

STS-3 Reentry

Final Conditions and Location
at Encounter.

STS-3: 30°56.9'N, 118°22.3'W.
Alt. = 185,322 ft.
Hdg. = 80.61°
Vel. = 15,634 ft/sec.

(Above data from T-20 min.
update)

C-141/KA0: 30°41.9'N,
118°14.7'W.
Alt. = 41,000 ft.
Hdg. = 80.5°
Ground Speed = 475 Kts

Time of Encounter

15:51:10 +02 UT
-00

Cross-track error of C-141 ≤
0.4 n. mile.

Wind: 58 kts/253° steady.

At takeoff, precise STS
reentry trajectory not yet
available.

Expected encounter point
approx. 150 nautical miles
south of Los Angeles, approx.
80 nautical miles west of
Ensenada.

Vandenberg/WTR obtained C-141
clearance into restricted area
W-291.

06:20 PST, received 1st
trajectory update via USAF HF
Net from Dryden Control.

Changed C-141 track 1 to 3
n.m. south due to change in
STS heading.

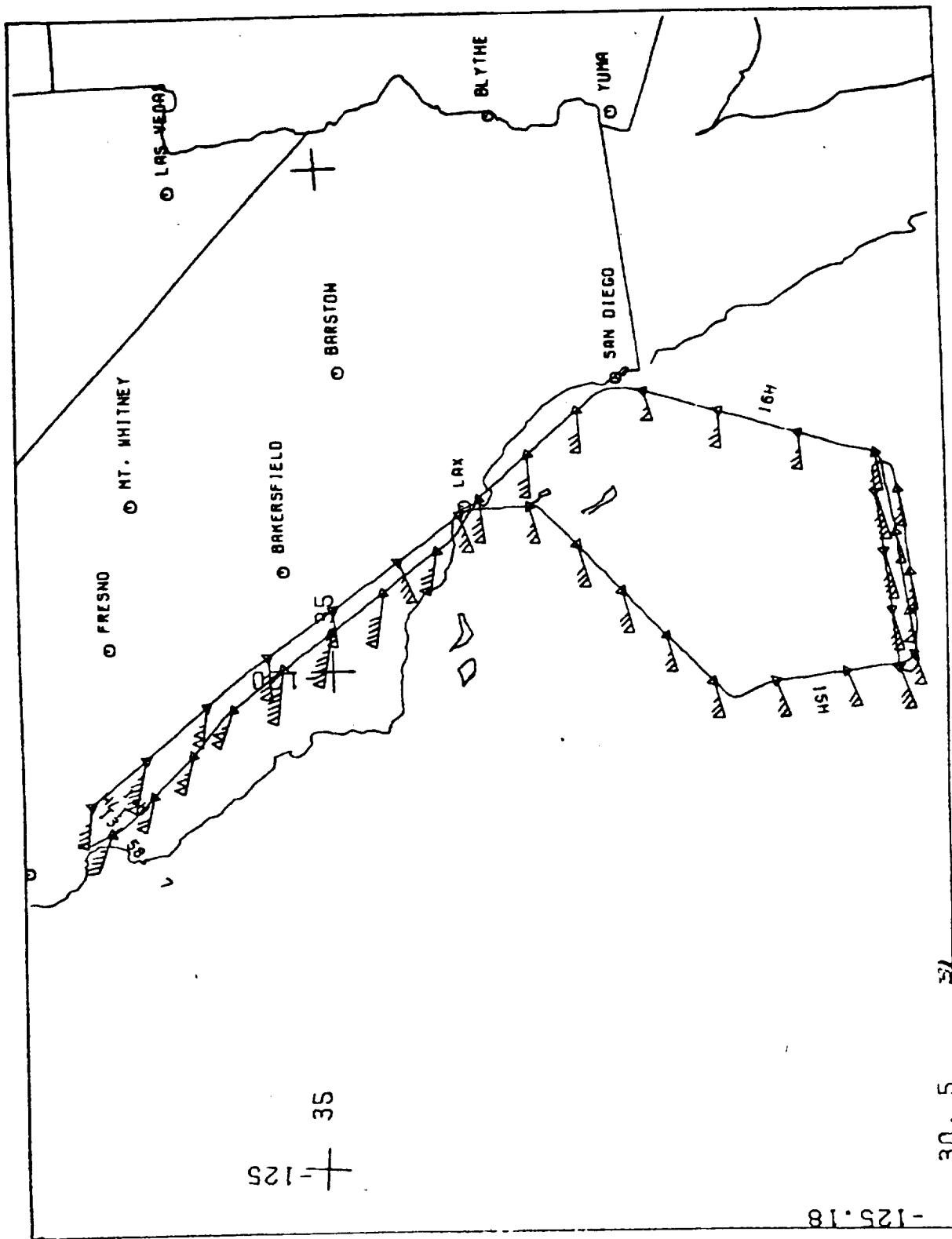
15:09-15:25 UT - 1st practice
run.

~15:30 UT (~T-20 m) - 2nd
trajectory update (results of
de-orbit burn) via USAF HF
Net.

Shifted aircraft track 5-6
n.m. north; Δ heading.

Continuous radar reports
on C-141 track.

Successful STS-3 Imaging



IRIS 04
 13157137 TO 481 01 0 UT. SCALE 1:12.96E+06 TIME TICS EVERY 5.00 MINUTES
 MARCH 20, 1982 MOFFETT LOCAL

FIGURE 1

APPENDIX 7.0

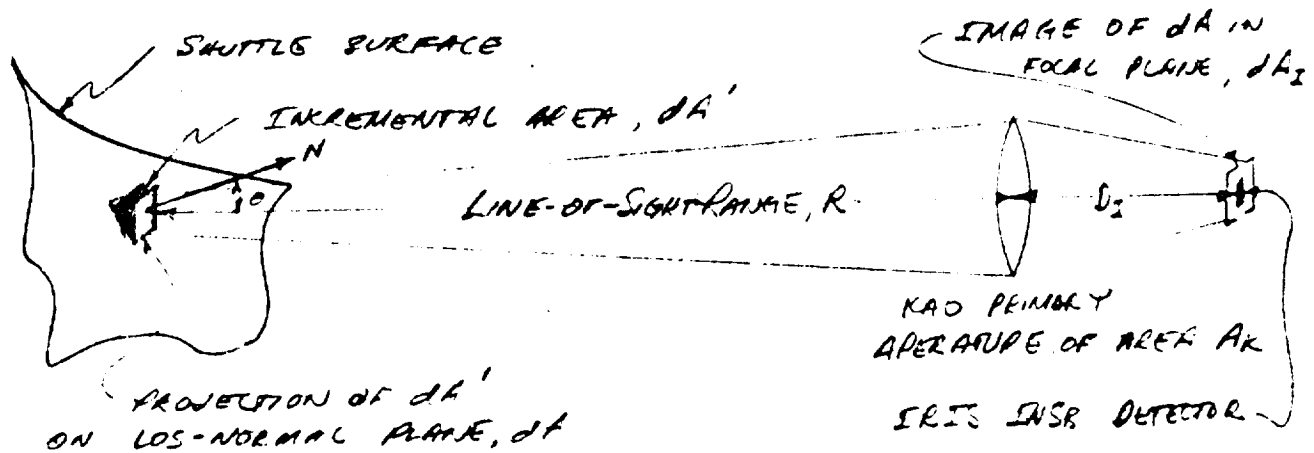
IRIS RADIOMETER ANALYSIS REPORT

W. Davy

7.0

KAO TELESCOPE

The KAO telescope and image plane array have been analyzed as a radiometer to identify critical parameters and assist in the establishment of the data reduction procedure. The telescope analysis is based on the model shown schematically below:



Define S^* as the surface emissive power of the Shuttle surface in the IRIS band. Then the power in the beam intercepted by the primary aperture is given by

$$P = \left(\frac{S^*}{\pi} \right) \cos \theta \left(\frac{A_K}{R^2} \right) dA'$$

Here, θ is the angle between the line-of-sight vector and the body-normal vector, N . If the KAO telescope optical train has a transmission τ_K , then the power in the focal plane image is simply

$$P' = P \tau_K = \frac{\tau_K S^* \cos \theta A_K dA'}{\pi R^2}$$

As indicated in the sketch, the area that is imaged in the focal plane is the area dA that is projected on a line-of-sight normal plane by dA' . The area image is given by

$$dA_I = M^2 dA$$

where M is the linear magnification of the telescope. This term is given by $M = D_I/R$, where D_I is the distance from the aperture to the focal plane. Using the lens equation:

$$\frac{1}{D_I} + \frac{1}{R} = \frac{1}{L_F}$$

OR

$$1 + \frac{D_I}{R} = \frac{D_I}{L_F}$$

where L_F is the effective focal length of the KAO telescope. Since $L_F \ll R$, then $D_I/L_F = 1$, so we can write

$$M = L_F/R$$

$$\text{Thus, } dA_I = (L_F^2/R^2) dA$$

The fraction of the transmitted power, P , that is converted to detector signal is given by the ratio (A_D/dA_I) where A_D is the detector area. If P_S is the power converted to signal, then

$$P_S = P \left(\frac{A_D}{dA_I} \right) = \frac{\tau_k \mathcal{B}^* \cos \theta A_k dA'}{\pi R^2} \left(\frac{A_D}{dA_I} \right)$$

Substitution and cancellation gives

$$P_S = \frac{\tau_k \mathcal{B}^* \cos \theta A_k dA' A_D}{L_F^2 dA}$$

The relation between dA and dA' is simply

$$dA = \cos \theta dA'$$

Also the telescope aperture area is

$$A_K = \frac{\pi D_K^2}{4}$$

Where D_K is the diameter of the primary aperture. Substitution of these expressions gives

$$P_S = \frac{1}{4} \tau_K S^* A_D \left(\frac{D_K}{L_F}\right)^2 = \frac{1}{4} \tau_K S^* A_D f_K^2$$

Where f_K is the effective F-Number of the KAO telescope, (D_K/L_F) . The signal conversion is modeled by the responsivity, R , so that

$$S = R P_S = \frac{1}{4} R \tau_K S^* A_D f_K^2$$

For brevity, define

$$R = 1/4 A_D R$$

or

$$S = R K f_K^2 *$$

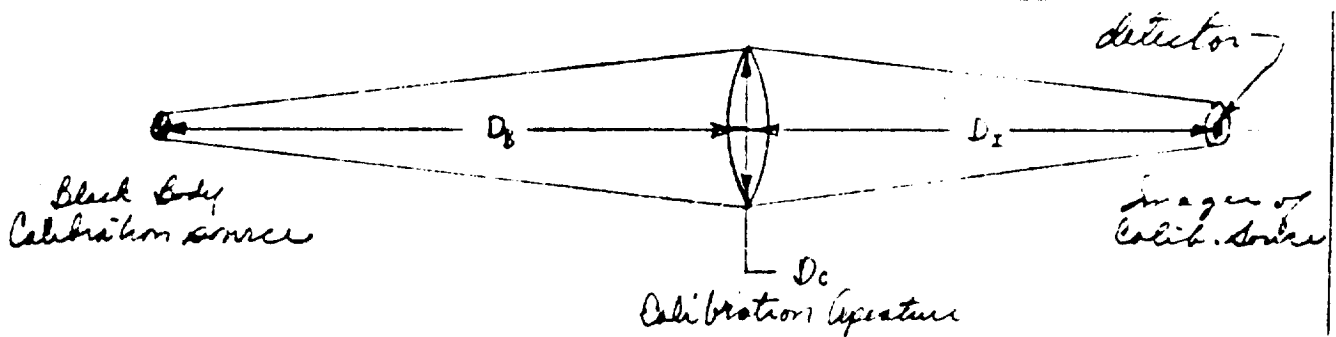
If the signal processing electronics have an electronic gain, G , then the digital signal, C , that is stored to memory from the i th detector is

$$C_i = G_i S_i = G_i R_i \tau_K f_K^2 S^*$$

The responsivity, R_i , in the above equation has to be determined by calibration against a blackbody source.

7.1 CALIBRATION

Radiometric analysis of the calibration procedure is based on the model sketched below:



Let the emissive power from the standard source be defined as $B^*(TC)$. Then,

$$B^*(T_c) = \int_{\lambda_1}^{\lambda_2} B_{\lambda}(T_c) d\lambda$$

where λ_1 and λ_2 are the wavelength limits of the IRIS bandpass filter, and $B_{\lambda}(T_c)$ is the Plank function for the calibration temperature T_c . A development similar to the one above for the KAO telescope results in the following equation:

$$C_{ic} = \tau_{ic} R_{ic} f_c'(f_c')^2 B^*$$

In this equation f_c' is a "modified" F-number given by $f_c' = f_c / \sqrt{\tau_{ic}}$ and the subscript C refers to calibration. Now introduce the concept of a relative response defined as

$$R_i = R_i / R_c$$

where R_* is the responsivity of the reference detector. Thus, we can write the calibration signal equation as

$$C_{ic} = G_{ic} l_i R_* \tau_c (f_c')^2 B^*$$

And for the reference detector we can write

$$C_{*c} = G_{*c} R_* \tau_c (f_c')^2 B^*$$

Note that for this detector $\eta = 1$ by definition. Ratioing the above two equations, we obtain the expression for l_i :

$$\begin{aligned} \text{OR} \quad \frac{C_{ic}}{C_{*c}} &= \frac{G_{ic} l_i}{G_{*c}} \\ l_i &= C'_{ic} / C'_{*c} \end{aligned}$$

where C'_{ic} is the recorded calibration signal normalized by the electronic gain, i.e., $C'_{ic} = C_{ic}/G_{ic}$. Using the above calibration equation, we can obtain an expression for R_* :

$$R_* = C'_{*c} / l_i R_* \tau_c (f_c')^2 B^*$$

The responsivity of the reference detector R_* can be obtained from the equation above as

$$R_* = C'_{*c} / \tau_c (f_c')^2 B^*$$

Substitution of these expressions into data signal equation gives

$$C'_d = \frac{C_d}{G_d} = l_i \left(\frac{C'_{*c}}{\tau_c (f_c')^2 B^*} \right) \tau_k f_k^2 S'^*$$

This equation now allows us to write an expression for S^* , viz:

$$S^* = \left(\frac{C'_s}{C'_r}\right) \frac{1}{f_n} \left(\frac{T_c}{T_r}\right) \left(\frac{f_c}{f_r}\right)^2 B^*(T_c)$$

Thus, we see that the emissive power of the Shuttle surface can be written as a product of terms: The ratio of data to reference calibration signals inversely scaled by the relative response multiplied by the transmission ratio and the F-number ratio squared. This product then multiplies the emissive power of the calibration source. The question arises as to what temperature is to be used for the blackbody source. If the detectors have a linear response, i.e., $R_i = \text{constant}$, then it does matter because the ratio $C'_c/B^*(T_c)$ is a constant. Analysis of the absolute calibration data, however, indicates a nonlinearity of about 10%. Hence, if we choose to use a mean responsivity, we could introduce a small error (5% max.). However, if we include in our data reduction program a table of responsivity, R_* , or its equivalent $R_* T_c f_c'^2 = C'_c/B^*(T_c)$, as a function of emissive power, then a simple iteration procedure can be used to reduce this error significantly.